



**TransAlta
Utilities**

GASIFICATION OF CANADIAN COALS
USING PILOT PLANT
PRESSURIZED GASIFIER
[Part of the program of the Federal
Panel on Energy R&D (PERD)]

Final Report

by

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EXECUTIVE SUMMARY

Coal gasification in combination with combined cycle power (IGCC) generation is a new technology which offers the potential for the more efficient and environmentally acceptable utilization of coal for power production.

When this project was proposed, only limited testing of Canadian coals for gasification applications had been carried out. To improve the background database on the gasification of Canadian coals, bench scale gasification tests were carried out at the University of British Columbia using the UBC pressurized fluid bed gasifier. One Canadian sub-bituminous coal, three Canadian bituminous coals and one American bituminous coal, for comparison purposes, were used as feedstocks.

The tests established the effects of air/coal ratio, temperature and operating pressure on gas heating value, gas yield, carbon conversion, cold gas efficiency and other performance indicators. The results showed that all the Canadian coals could be gasified and indicated the conditions for producing gases of the required heating value for IGCC. For the sub-bituminous coal, the test results were comparable with previous pilot scale test results.

RÉSUMÉ

La gazéification du charbon, jointe à la production d'énergie à cycle combiné, est une nouvelle technique qui offre la possibilité d'utiliser le charbon pour produire de l'énergie d'une façon efficace et conforme aux normes établies en matière d'environnement.

Lorsque l'on a soumis le projet, seules quelques expériences sur le procédé de gazéification avaient été effectuées avec des charbons d'origine canadienne. Afin d'améliorer la base de données sur la gazéification des charbons d'origine canadienne, on a mené des études en laboratoire à l'université de la Colombie - Britannique à l'aide d'un réacteur sous pression à lit fluidisé. En vue d'établir une comparaison, on a alimenté le réacteur avec différents types de charbon: un charbon subbitumineux et trois charbons bitumineux d'origine canadienne ainsi qu'un charbon bitumineux d'origine américaine.

Les études en laboratoire ont permis d'évaluer les effets de la température, de la pression opératoire et de la proportion air-charbon sur le pouvoir calorifique ainsi que le rendement des gaz, la transformation du carbone, le rendement des gaz froids en plus de fournir d'autres indicateurs de rendement. Les expériences ont également montré que tous les charbons d'origine canadienne sont en mesure d'être gazéifiés. En outre, on a pu déterminer les conditions qui sont nécessaires pour produire des gaz dont la puissance calorifique puisse satisfaire aux exigences de la production d'énergie à cycle combiné. En ce qui concerne le charbon subbitumineux, les résultats sont analogues à ceux qui ont été obtenus lors d'expériences précédentes.

TABLE OF CONTENTS

	<u>PAGE</u>
Executive Summary	(i)
Résumé	(ii)
Table of Contents	(iii)
 PART 1 - INTRODUCTION	 1
 PART 2 - TECHNICAL DISCUSSION	 1
2.1 OBJECTIVE	1
2.2 BACKGROUND	2
2.3 SCOPE AND WORK PLAN	3
 PART 3 - CONCLUSIONS	 7

FIGURE

Figure 1	Process Flow Diagram	4
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APPENDIX -	GASIFICATION OF CANADIAN COALS IN A 0.1 M DIA. SPOUTED/FLUID BED PRESSURIZED GASIFIER The University of British Columbia, March 1989.	
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1.0 INTRODUCTION

The use of coal gasification technology in combined cycle power generation plants has been identified as a potential major application of this technology. At present, considerable work on the development of coal gasification combined cycle technology is being conducted in Canada and overseas by both the government and the private sector. If developed and implemented, coal gasification technology not only is a more cost efficient means of electric power generation but also a more environmentally acceptable means.

In Canada, development of coal gasification technology has been pursued by federal and provincial organizations as well as a number of companies from the private sector. Various research programs have been undertaken but to date there has been little study of the performance of Canadian coals in continuous operation in pressurized gasifiers other than the pilot plant scale test carried out at the KRW Energy Systems Waltz Mill Plant in June 1987.

This project was undertaken to provide data on the gasification of four Canadian coals and on the factors which influence efficiency and performance for the fluidized or fluidized-spouted bed dry ash mode gasifier as typified by the KRW technology.

2.0 TECHNICAL DISCUSSION

2.1 OBJECTIVE

The objective of the work program was to develop technical data on the gasification of the selected four Canadian coals. Tests

were carried out over a range of temperatures, coal feed rates and air/steam or oxygen/steam rates to characterize each coal. Gas quality, yield, steam and carbon utilization, and gasifier efficiency are determined as functions of process variables.

2.2 BACKGROUND

In the three years prior to this work, TransAlta Utilities had conducted several studies on the gasification of western coals and its application. This work was supported by CANMET, the Office of Coal Research and Technology, Alberta Department of Energy and Natural Resources and other private sector participants. Also in mid-1987, a test run of Alberta sub-bituminous coal was carried out using the KRW pilot plant.

At the same time, UBC had developed nearly ten years of gasification expertise and experience in the operation of a continuous bench scale gasification facility to produce a low carbon monoxide gas. Simple modifications to this facility enabled it to be run as an air/oxygen blown gasification system with a reactor configuration which closely modeled the fluidized bed design. These low cost modifications resulted in a pressurized gasification system that could be used to develop the required data base on which Canadian coals are most suitable to IGCC operations.

These characteristics cannot be predicted either from prior atmospheric pressure tests because of the uncertainties with respect to the order of the steam-oxygen-coal reaction in the presence of simultaneous devolatilization as pressure increases, or from the limited tests done to date at continuous elevated pressure operation in steam gasification because of the important role of oxygen. The information from the proposed test programs can be of

use to both coal companies attempting to export their products and utilities which are concerned with IGCC applications within Canada.

2.3 SCOPE AND WORK PLAN

231 SCOPE OF WORK

TransAlta worked closely with the University of British Columbia and Monenco Consultants to develop the overall test plan. UBC conducted a series of gasification tests on the selected coals at various air/coal ratios, oxygen/coal ratios and operating pressures. A process flow diagram of the bench scale gasification facility is provided in Figure 1.

Representatives from CANMET, TransAlta, Monenco and the private sector attended regular progress meetings at the University of British Columbia throughout the test period. They were briefed on the status and latest results of the test program. This program consisted of the following tasks which are expanded upon in the following subsection:

- Task 1 - Modification of Pilot Plant Gasifier
- Task 2 - Coal Selection
- Task 3 - Coal Sample Preparation
- Task 4 - Gasification Tests (Air)
- Task 5 - Gasification Tests (Oxygen)
- Task 6 - Report Preparation

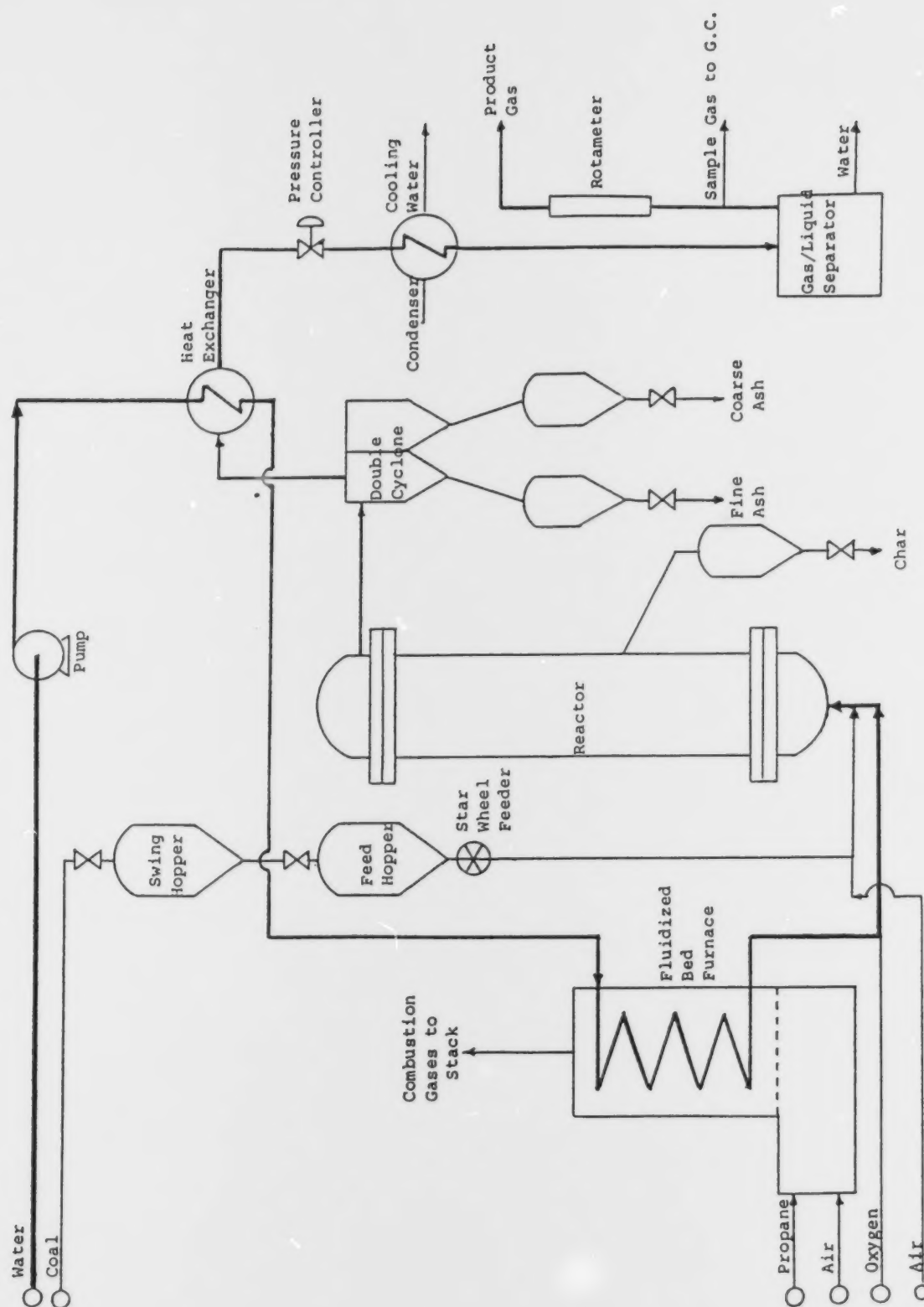


Figure 1; Process Flow Diagram

Task 1 - Modification of Pilot Plant Gasifier

The existing facility was designed to conduct steam gasification tests. To enable it to be used for the air or oxygen blown fluid bed gasification experiments required in this program, the following modifications were carried out:

- o inlet lines rebuilt to enable the injection of air and/or oxygen;
- o flow meters for air and oxygen installed; and
- o distributor to ensure fluidization of the bed installed.

Task 2 - Coal Selection

After review by all participants, the following five coals were selected for testing:

- o Pittsburgh No. 8, Pennsylvania. Reference coal. This is a high volatile, bituminous coal used by many investigators as a reference coal in gasification studies or as a feedstock to assess gasifier capability.
- o Highvale, Alberta. This is a sub-bituminous coal used in the previous KRW pilot plant tests where successful gasification results were obtained.
- o Coal Valley, Alberta. This is a high volatile, bituminous coal.

- o Byron Creek, British Columbia. This is a medium volatile, bituminous coal.
- o Prince Hub, Nova Scotia. This is a high volatile, bituminous coal.

Task 3 - Coal Sample Preparation

About one tonne sample of each coal was obtained. These samples were crushed and screened to give the required 0.3 to 3 mm fraction. For each sample, the following properties were determined:

- o Proximate analysis;
- o Ultimate analysis;
- o Ash analysis;
- o Heating value; and
- o Free swelling index.

Task 4 - Gasification Tests (Air)

For each of the coals, gasification tests were carried out under steady state conditions with variations in coal feedrates, air/coal and steam/oxygen ratios and gasifier operating pressure.

During these tests, the following measurements were taken:

- o gasifier operating temperature;
- o all flow rates; and
- o gas composition.

From these measurements, the following parameters were calculated:

- o gas heating value;

- o carbon conversion; and
- o mass balance.

Task 5 - Gasification Tests (Oxygen)

All the steps described in Task 4 were repeated using oxygen rather than air for Highvale and Coal Valley coals and using oxygen enriched air for the Byron Creek, Prince Hub and Pittsburg No. 8 coals.

Task 6 - Report Preparation

UBC prepared a final report which includes all the test results and coal analyses. The report shows the effect of the varied parameters on the characteristics of the resultant raw gas. The report also identifies conditions required for improved gasification of these coals.

Comparisons of the test results with those obtained using the UBC equilibrium model are presented. Also for the Highvale coal, a comparison with the KRW pilot plant test results is given. The UBC report is included in the Appendix.

3.0 CONCLUSIONS

The main conclusions of this report are:

- o Highvale, the most reactive coal, produced the strongest gas at the highest feed rate and lowest temperature. At the same air/coal ratio gas heating value was about 0.6 to 0.8 MJ/m³ higher for Highvale than for any other coal.

- o Coal Valley, Byron Creek, Prince Hub and Pittsburg Seam coals produced the same gas heating value at a given oxygen/coal ratio.
- o Within limits, all coals could be gasified without pre-treatment in the spouted/fluidized bed. Although optimal conditions were not reached for all coals, results showed consistent trends which, with limited extrapolation, predict the conditions necessary for IGCC gas production.
- o With less reactive (higher rank) coals, gasified throughput is lowered, and operating temperatures must be raised to produce suitable gases. All coals produced bed residues which were free-flowing and did not contain agglomerates under optimum conditions.
- o With increased air/coal feed rate, the gas heating value decreased while both the gas yield and carbon conversion increased.
- o With oxygen, greater gas heating values were achieved and carbon conversion increased probably due to the higher gas temperature.
- o Operating pressure had little effect on gasifier performance.
- o Gases from the Highvale and Coal Valley coals were in only rough agreement with equilibrium predictions. Hydrogen contents were typically 25% lower than predicted, while CO and CO₂ contents were considerably closer.
- o Gases from the Byron Creek and Prince Hub coals were low in H₂ with H₂/CO ratios well below the predicted

equilibrium levels. Thus gases leaving the gasifier were not in equilibrium.

- o The caking nature of Byron Creek and Prince Hub coals necessitated a switch to bottom feeding. In the range of smoother operation of the gasifier bed, residues were free flowing and without agglomerates. Smooth operation was only possible within a limited range of conditions. Under such conditions the bed operated smoothly, and the residual material from the bed contained no agglomerates.
- o When the KRW data for Highvale coal were corrected for the higher nitrogen content, gas heating values were comparable to those observed in the present tests. Gas yield and H_2/CO ratios were also comparable.

APPENDIX

GASIFICATION OF CANADIAN COALS IN A 0.1 M DIA.
SPOUTED/FLUID BED PRESSURIZED GASIFIER
The University of British Columbia, March 1989

GASIFICATION OF CANADIAN COALS IN A 0.1 M DIA.
SPOUTED/FLUID BED PRESSURIZED GASIFIER

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Summary

This report summarizes gasification tests done in a 2-6 kg M.A.F. coal/h bench scale gasifier with five coals: Highvale, Coal Valley, Byron Creek, Prince Hub and Pittsburgh Seam. For the former two coals most experiments were done at 7-9 atm pressure with a blast containing air and steam, although some tests were also done at pressures of 5 atm and 14 atm. An oxygen/steam blast was also used done with some coals. The effects of air/coal ratio, temperature and operating pressure are established on gas heating value, gas yield, carbon conversion, cold gas efficiency and other performance indicators. Gas analyses are compared with composition expected at equilibrium.

Highvale coal, the only sub-bituminous coal tested, is most readily gasified producing gases of heating value of about 4.7 MJ/m^3 at an air/M.A.F. coal ratio of 4 compared to $3.8\text{--}4 \text{ MJ/m}^3$ for the bituminous coals. Carbon conversions at the above air/coal ratio were also higher for Highvale coal in spite of the 100°C lower temperature. In oxygen/steam experiments with Highvale and Coal Valley coals heating values of about 10 MJ/m^3 were obtained. Gas yield results were comparable for both coals. On a plot of gas heating value versus N_2/coal ratio, the KRW test results on Highvale which were obtained at a throughput a factor of forty greater than in the present work were found to match the experimental values. This provided further confirmation of the validity of the present experimental results.

For Highvale and Coal Valley coal the H_2 contents of the produced gases were found to be about three-quarters of the values expected if the gases were in true equilibrium at the reactor temperature and pressure. CO and

CO₂ values were closer to predictions.

For the Byron Creek, Prince Hub and Pittsburgh Seam coals, most experiments were carried out at 4-6 atm pressure with a blast containing air and steam. The effects of oxygen/coal ratio and temperature were established on gas heating value, gas yield, carbon conversion, cold gas efficiency and other performance indicators.

These are all caking coals of bituminous rank and less reactive than either Highvale or Coal Valley. Higher operating temperatures of up to 900°C were required. These were achieved by increasing the oxidant/coal ratio primarily by reducing the coal rate. This resulted in consumption of some of the product hydrogen with a corresponding decrease in the gas heating value and cold gas efficiency. Gas heating values of around 3.7 MJ/m³ were achieved. The swelling nature of the coals presented operating difficulties, mainly from the formation of char agglomerates which would eventually plug the reactor. These problems were overcome in large part by feeding coal in with the gases at the bottom of the reactor into the hot combustion zone. The low reactivity and swelling nature placed limits on the ranges of parameters such as feed rate that could be employed so that the optimum conditions for gasification were not achieved in all cases.

The results for all three caking coals were remarkably similar. The gas heating value versus oxygen/coal ratio data for these coals fell on a common line with the Coal Valley data except that higher oxygen/coal ratios were necessary for the former. The results clearly indicate the conditions for producing gases of the required heating value of IGCC. Ranges in which the spout/fluid bed can operate with a free flowing bed on coals with F.S.I. up to 7 have been established.

INDEX

	Page No.
Summary	2
Introduction	5
Experimental Apparatus and Procedures	6
Gasifier Performance Factors	14
Comparison of Produced Gas Composition with an Equilibrium Model	15
Results and Discussion	15
Highvale Coal	17
Coal Valley	35
Byron Creek Coal	48
Prince Hub Coal	60
Pittsburgh Seam Coal	71
Comparison of Gasification Results with Different Coals	76
Conclusions	81
References	87
Appendix A Steady State Material Balances	
Appendix B Test Results for Typical Run - Run TA75	
Appendix C Equilibrium Model	

Introduction

Utilities which generate power in thermal plants, and coal companies looking to expanded markets, are actively considering the option of integrated coal gasification combined cycle technology (IGCC) for power generation. The advantages of IGCC versus conventional pulverized coal firing have been discussed in numerous studies⁽¹⁻³⁾. In IGCC, carbonaceous feeds are gasified with air and steam, or with oxygen and steam, at elevated pressures to produce a clean burning fuel gas which can be combusted in a gas turbine, which, combined with the steam turbine, produces electrical power at high efficiency. To date there has been little study of the performance of Canadian coals in continuous operation in pressurized gasifiers. This project was undertaken to provide data on the factors which influence efficiency and performance for the fluidized or fluidized-spouted bed dry ash mode gasifier typified by the KRW unit⁽³⁾.

Four coals from across Canada, and one U.S. coal were studied. This report covers the tests on all the coals tested, and thus includes material from an Interim Report⁽⁴⁾ which was issued in September 1988 and covered the first two coals gasified.

The U.B.C. Pressurized Coal Gasification pilot plant is an 0.1 m dia. unit capable of continuous operation at pressures to over 20 atm. Coal of 1-4 mm in size is fed at roughly 2-6 kg/h and gasified in a mixture of air and steam or oxygen and steam to produce a combustible gas. Experiments are carried out over a range of temperatures, coal feed rates and blast compositions to characterize the coal. Gas quality, yield, steam and carbon utilization and gasifier efficiency are determined as functions of process variables.

Experimental Apparatus and Procedures

Coal gasification tests were carried out in the pressurized pilot plant unit located at the University of British Columbia. The pilot plant facility was principally designed to conduct steam gasification tests and as part of this program modified to allow the addition of air or oxygen such that air-blown or oxygen-blown gasification experiments could be performed. The unit is convenient for the study of the effects of operating parameters on gasification.

A process flow sheet of the pilot plant is shown in Figure 1. Table 1 lists specifications for the gasifier and gas treatment facilities. The configuration shown in Figure 1 is for coal feeding at the bottom of the reactor which was used for the caking bituminous coals. For Highvale, the sub-bituminous coal, and Coal Valley a non-caking bituminous coal, top feeding was used as described in the Interim Report⁽⁴⁾. With the caking coals (F.S.I > 4.5) operating difficulties were encountered with the top feeding system. The caking coals swelled as they became heated to reactor temperature. This produced low density char particles which tended to stick together to form a continuous mass bridging the whole reactor. A plug would form in the upper section of the reactor and result in a large pressure drop across the reactor. Fluctuations in the flow of both the coal and oxidant would occur. The bed would collapse and large temperature excursions would result as the immobilized residual char was burnt. These difficulties led to a change of the coal feed point so that the coal would be introduced at the bottom of the reactor. This essentially solved the operating difficulties, although other adjustments in experimental procedure and

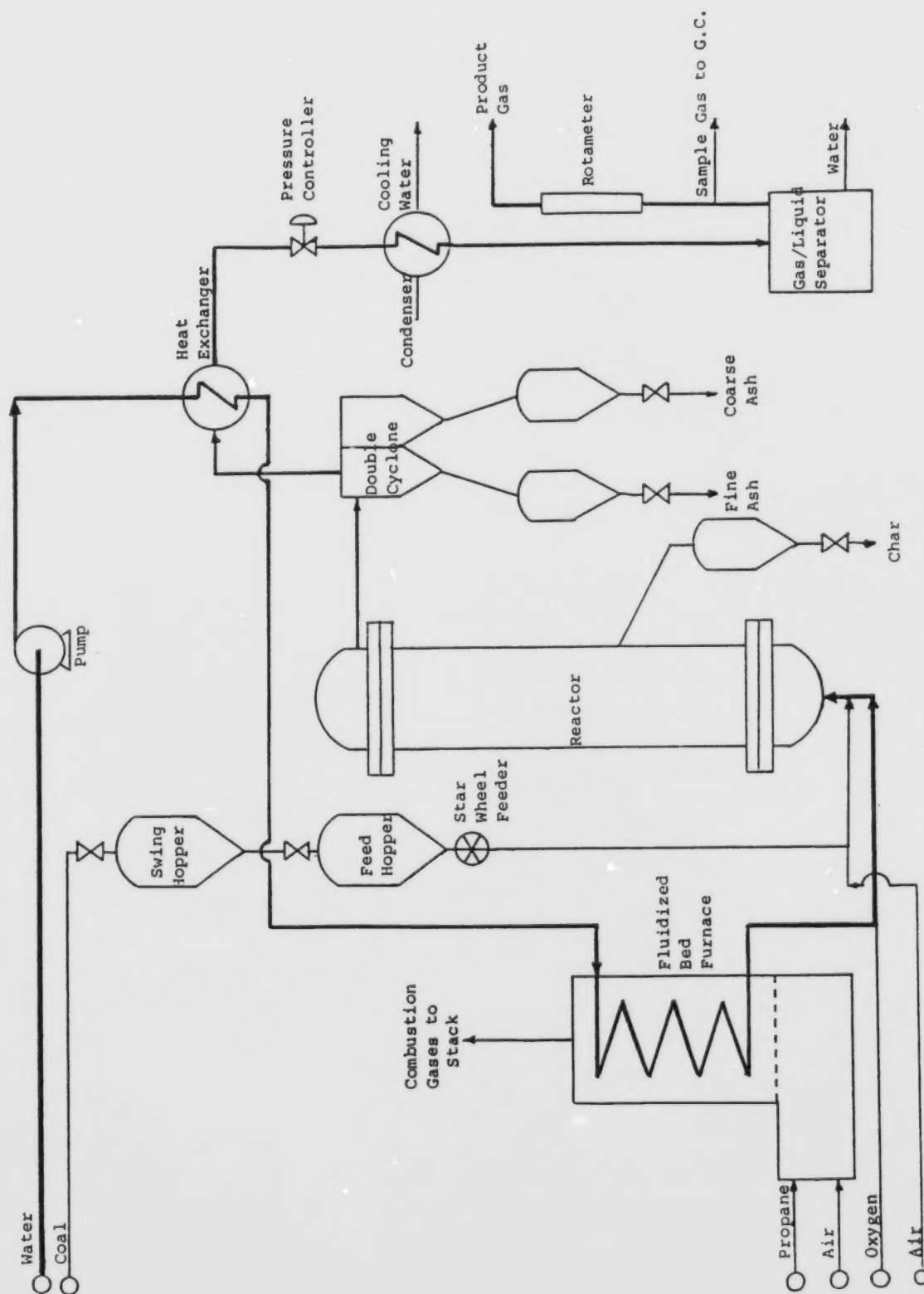


Figure 1: Process Flow Diagram

TABLE 1 Specifications of Gasifier Plant

Gasifier Unit

Shell Sched. 160 Carbon Steel, 30 cm. outside diameter
Inside diameter 10 cm. Incolloy Tube
Lining - Insulating wool and castable refractory
Overall height 162.6 cm.
Cone height 15 cm.
Bed overflow port height 65 cm. from apex

Fluid Bed Furnace

Propane fired, fluidized sand bed
Tube diameter 2.5 cm. material 316 stainless steel
Typical sand bed temperature 900°C

Coal Feed

Hoppers (2) materials - Sched. 80 Carbon Steel
Overall height 56 cm., cone height 26 cm.
Rotary valve feeder

Cyclone

Cardiff type double cyclone
Inside diameter 10 cm., collector diameter 5 cm.
Height 25.5 cm.

Heat Exchanger

Length 140 cm.	U-tube type
Shell inside diameter 17 cm.	Tube diameter 2.5 cm.

Condenser

Length 86 cm.	6 Tubes
Shell inside diameter 11 cm.	Tube diameter 2.5 cm.

material flow rates were needed to maintain adequate bed circulation and heat balances.

A detailed drawing of the reactor is shown in Figure 2a. It consists of an inner Incolloy tube, 100 mm in diameter, positioned above a conical refractory base. There are four electrical heaters mounted on the outside of the Incolloy tube. The inner tube is enclosed in a 0.3 m diameter steel shell with refractory and fibrous insulation occupying the space between the tube and outer shell. With this arrangement, the inner tube can operate at a very high temperature but at essentially zero pressure, while the outer shell withstands the elevated operating pressure at a much reduced temperature. There are thermocouples located 150 mm apart along the length of the reactor and a bed overflow port 0.7 m above the apex of the cone. During gasification, the reactant gases enter through a 10 mm nozzle at the base of the reactor and form a spout at the centre of the reactor entraining the bed particles upward. Above the top of the bed the particles fall to the side and flow downward in a moving bed fashion. On reaching the cone the particles are again entrained by the spout. The bed circulation results in a fairly uniform temperature distribution and good contact between the coal and reactants. The coal particles circulate until they are gasified or entrained overhead as fines with the product gas leaving the reactor.

In the bottom feeding configuration, coal is fed from two pressurized coal hoppers by means of a star wheel feeder which has a variable speed drive to allow changes in coal feed rate. The coal is conveyed pneumatically by the air used for gasification and enters the reactor through a central guide tube at the apex of the cone. Details of the piping connections for feeding the coal reactants are shown in Figure 2b. Process

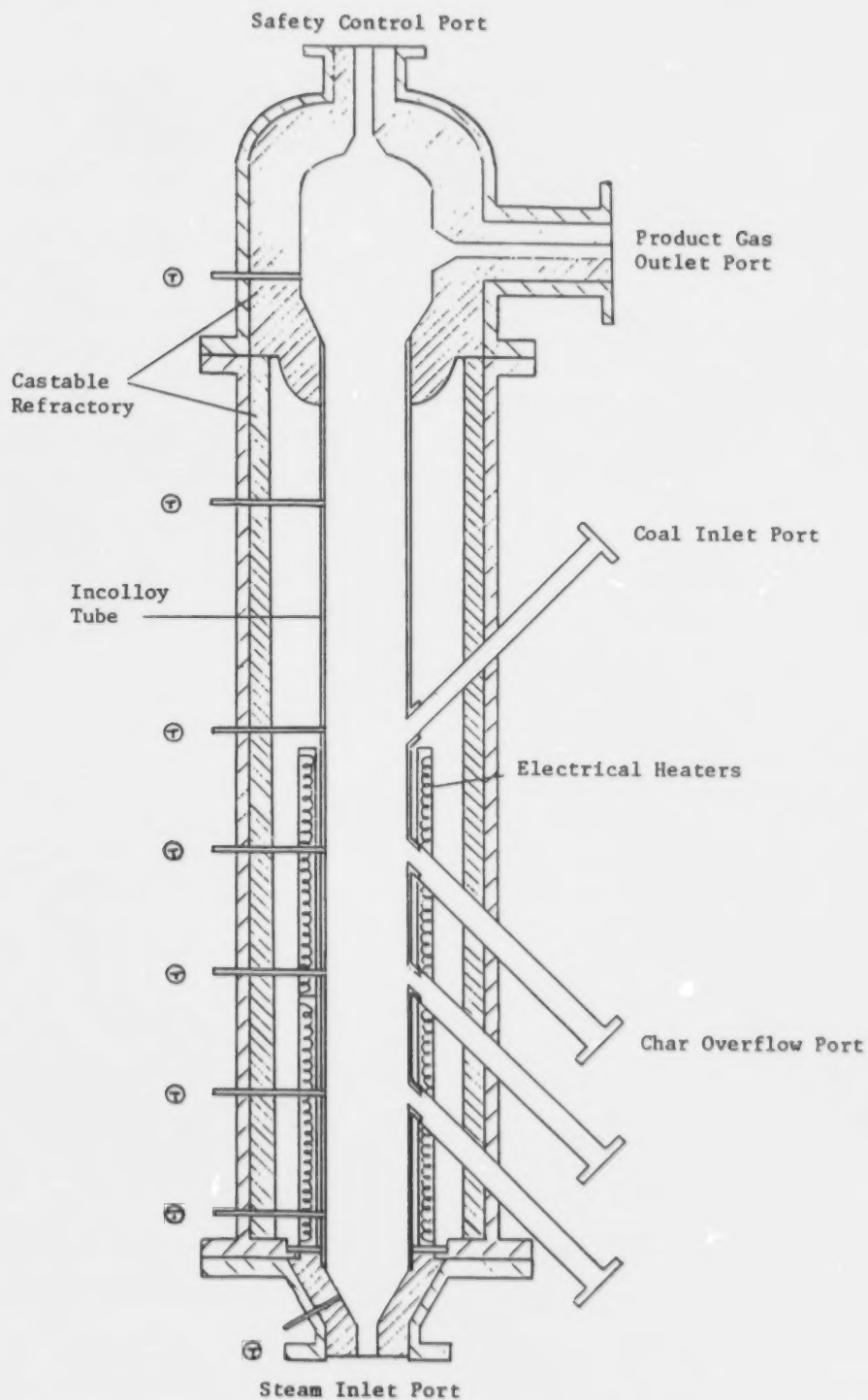


Figure 2a: Reactor Detail

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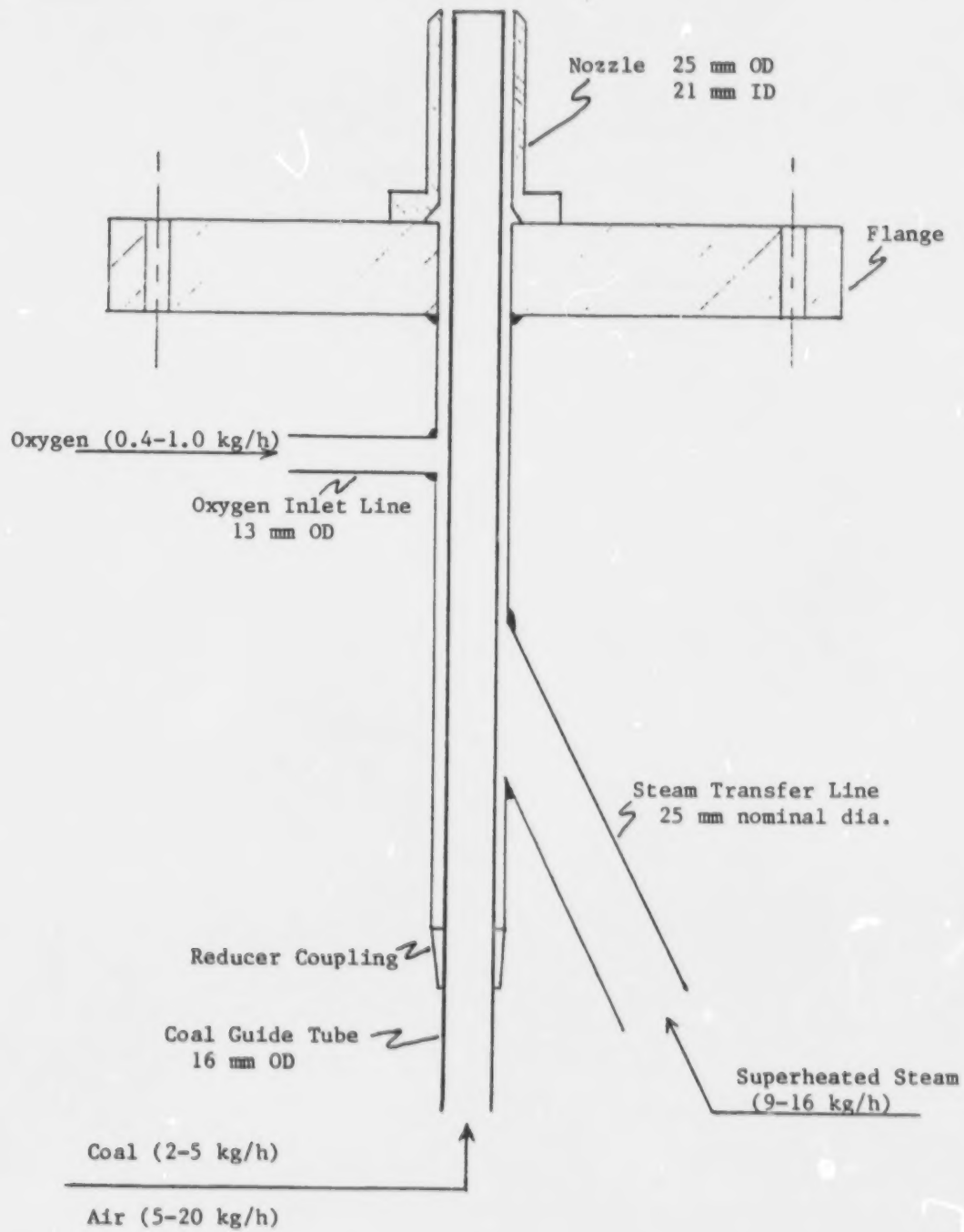


Figure 2b: Reactor Bottom Connection

feed water is delivered by a diaphragm pump to a shell-and-tube heat exchanger where it is heated by the reactor product gas. The process water continues to a propane-fired furnace and becomes vaporized and superheated by heat transfer from a fluidized sand bed which is heated by the flue gas from propane combustion. The superheated steam enters the reactor through a concentric tube which encircles the coal guide tube. In tests where oxygen is added, the oxygen joins the steam flow just below the reactor bottom. The product gas leaves at the top of the reactor and passes through a double cyclone where coarse and fine ash are separated. The gas is then cooled in the heat exchanger by the process feed water. After depressurization, the product gas is further cooled to condense the excess water. A rotameter is used to measure the flow rate of gas and its composition is analyzed.

In a typical test the unit is first heated with a flow of air which conveys heat from the furnace to the reactor. The process water flow is then started and the air flow reduced slowly. When the reactor reaches a temperature of 300 to 400°C with only steam flow, an initial bed of 500 to 600 g of inert (1 mm dia. sand) is introduced. This causes a drop in the reactor temperature. After a period of time to allow temperature recovery, a flow of air is started to the coal conveying line and the star wheel feeder turned on. An initial charge of 1 kg of a reactive coal, either Highvale or Forestburg, is conveyed pneumatically into the reactor. Oxygen is introduced to initiate combustion. When a sufficiently high temperature is reached, the test coal is substituted for the reactive coal. The flow rates of steam, oxidant and coal are adjusted to obtain the desired bed temperature and fluidizing rates. The unit reaches steady state in 30 to 40 minutes depending on the operating conditions. Product gas samples are

withdrawn periodically for analysis by gas chromatography. The excess water is collected in a separate tank over a known time period. After completion of the entire test, the solids in the reactor, char overflow receiver, fine cyclone receiver and coarse cyclone receiver are collected, dried, weighed and measured for moisture, carbon and ash.

For tests on reactive non-caking coals the sand bed was not used. Gasification occurred in a bed of char and ash.

Gasifier Performance Factors

The following factors are used in this report to define various aspects of gasifier performance:

Gas Heating Value (GHV) = Heat of Combustion of Dry Product Gas (MJ/m³)

$$GHV = \left(\sum_i \Delta H_{c_i} \cdot Y_i \right) * n/v \quad \text{--- (1)}$$

where ΔH_{c_i} = heat of combustion at 15°C and 1 atm of species i (MJ/mol)

Y_i = mole fraction i in gas mixture (dry basis)

n, V = moles and volume of dry gas produced (15°C and 1 atm pressure)

i = H₂, CO, CH₄, and C₂H₄

Gas Yield (GY) = $\frac{\text{Vol. Dry Gas Produced (15°C, 1 atm pressure)}}{\text{Wt. Coal Used (M.A.F. basis)}}$

$$GY = V/M_c \text{ (m}^3/\text{kg M.A.F. coal)} \quad \text{--- (2)}$$

% Carbon Conversion = 100 * $\frac{\text{kg C in gas as CO, CO}_2, \text{CH}_4 \text{ and C}_2\text{H}_4}{\text{kg C in coal}}$

$$\text{--- (3)}$$

% Steam Decomposition = 100 * $\frac{\text{kg H}_2\text{O decomposed into H}_2}{\text{kg H}_2\text{O in steam and coal moisture fed}}$
 = 100 * $\frac{\text{moles H}_2 \text{ produced}}{\text{total moles H}_2\text{O in feed}}$

$$\text{--- (4)}$$

% Cold Gas Efficiency = 100 * $\frac{\text{Heat Produced by Combustion of Gases Produced}}{\text{Heat Produced by Coal Fed}}$

$$= 100 * (GHV * GY) / \Delta H_{c_{\text{coal}}} \quad \text{--- (5)}$$

where

$\Delta H_{c_{\text{coal}}}$ = heat of combustion per kg MAF coal (MJ/kg MAF coal).

Note that where other heat inputs occur, such as air and steam preheating, and electrical heat, the cold gas efficiency so defined is not an accurate reflection of efficiency.

Comparison of Produced Gas Composition with an Equilibrium Model

An equilibrium or kinetics-free model of the coal gasification process in the spouted bed gasifier was presented by Watkinson, Cheng and Lim⁽⁵⁾. This model has been used in the present research as a confirmation to the trends observed in the experiments. For each run the inlet feed coal rate and composition are provided, along with information on the blast flowrate and composition. The temperature, pressure and carbon conversion for the gasifier are also used as input data. The model then is used to calculate gas outlet composition and yields. The model equations are summarized in Appendix C.

Results and Discussion

The coals used in the tests, Highvale, Coal Valley, Byron Creek, Prince Hub and Pittsburgh Seam, were crushed and screened to -6 +16 mesh size (about 1 to 3 mm). Analyses of all five coals tested are shown in Table 2.

The results with the various coals showed similarities in gasification behaviour as well as some significant differences. For simplicity of presentation the results for each coal are discussed separately, and a comparison among all coals tested is made at the end. Mass and elemental balances for the tests are presented in Appendix A.

TABLE 2 Feed Coal Analysis

Coal as received	Highvale	Coal Valley	Byron Creek	Prince Hub	Pittsburgh Seam
Ultimate Anal., Wt. %					
Carbon	51.78	64.62	74.53	66.81	73.07
Hydrogen	3.27	3.93	4.42	4.50	4.80
Nitrogen	0.81	0.87	1.20	1.22	1.34
Oxygen	13.64	12.31	5.67	11.07	7.25
Sulfur	0.16	0.16	0.37	3.10	3.39
Chlorine	-	-	-	-	0.07
Total	69.66	81.89	86.19	86.70	89.92
Proximate Anal., Wt. %					
Volatiles	39.88	31.70	25.14	33.46	40.60
Fixed carbon	29.79	50.10	61.05	53.24	49.32
Moisture	18.45	7.60	1.19	4.45	1.94
Ash	11.88	10.60	12.62	8.85	8.14
Total	100.00	99.90	100.00	100.00	100.00
Calorific Value, cal/g	4823	6050	7228	7106	7363
(as rec'd basis) MJ/kg	20.19	25.33	30.26	29.74	30.82
Free Swelling Index	1.0	1.0	4.5	5.5	7.0
Rank	Sub-bit	H.V.Bit	M.V.Bit	H.V.Bit	H.V.Bit

Highvale Coal: Introduction

Highvale coal was the lowest rank, most reactive coal tested in this program. Analysis in Table 2 shows this high volatile sub-bituminous coal to contain almost 40% volatiles, and about 30% fixed carbon. As this was the first coal tested, and of greater immediate commercial interest, it was investigated more thoroughly than the other coals. Table 3 gives a summary of the test results for this coal. Included in this table are the results from the KRW tests on Highvale coal which are described in reference⁽⁶⁾.

Highvale Coal: Results of a Typical Experiment

In order to clarify the time-behaviour of the gasifier, and provide a context to discuss further results, one typical run will by first considered.

For this purpose Run TA75 has been chosen and the results of this run are presented in Appendix B. The approach of systems conditions, such as temperature and gas compositions to steady state values are presented. It is evident that within an overall test duration of three hours steady state can be achieved, as is confirmed by the mass balance data of Appendix A.

Highvale Coal: Effect of Air Coal Ratio

In general, increasing the air/coal or oxygen/coal ratio increases the gasifier temperature because this induces a greater amount of coal combustion.

Figure 3 shows a series of gasification results plotted versus the air/coal ratio. The gasifier temperature increases nearly linearly with the air/coal ratio. Temperatures were in the range 650°C to 900°C. As the

TABLE 3

SUMMARY OF RESULTS

HIGHVALE COAL

Run No		73	77	90	75.1	75.2	80
OPERATING CONDITIONS							
Pressure	Atm.	4.67	9.84	8.93	5.18	4.84	7.12
Temp	C	736	880	692	789	901	621
Coal feed	kgMAF/hr	7.83	8.98	6.90	5.02	3.87	5.33
H2O/MAF	kg/kg	0.94	1.68	3.16	0.96	1.07	1.83
Air/MAF	kg/kg	0	0	0	3.01	3.95	1.98
N2/MAF	kg/kg	0.16	0.15	0.25	2.60	3.41	1.83
O2/MAF	kg/kg	0.42	0.62	0.52	0.71	0.93	0.47
RESULTS							
C Conv.	Wt. %	55.8	97.4	75.2	90.4	101.4	52.7
Effic.	%	45.3	85.0	53.3	76.5	76.4	51.8
H2O Decom	kg/kgMAF	0.19	0.44	0.48	0.47	0.34	0.33
H2O Decom	Wt. %	19.8	26.0	15.2	49.0	31.5	18.2
DRY GAS ANALYSIS							
H2	Vol. %	31.4	37.3	39.1	20.6	15.5	23.9
N2	Vol. %	8.2	5.5	9.3	49.8	56.1	44.6
CH4	Vol. %	4.1	2.9	4.1	1.8	1.5	2.5
CO	Vol. %	36.4	34.9	6.7	14.6	14.7	18.7
CO2	Vol. %	19.9	19.2	40.4	13.1	12.1	10.2
C2H6	Vol. %	0	0.20	0.26	0.10	0.03	0.12
HHV	MJ/m3	10.25	10.47	7.67	5.25	4.47	6.51
Gas yield	m3/kgMAF	1.28	2.35	2.01	4.22	4.96	2.31
H2/CO	mol/mol	0.9	1.1	5.8	1.4	1.1	1.3
WET GAS ANALYSIS							
H2O	Vol. %	42.2	39.7	62.4	12.6	15.6	44.7
EQUILIBRIUM MODEL RESULTS (DRY GAS)							
H2	Vol. %	44.0	45.6	46.0	23.0	18.8	30.2
N2	Vol. %	6.7	4.8	8.3	48.3	54.0	40.9
CH4	Vol. %	1.14	0.24	0.59	0.24	0.01	3.43
CO	Vol. %	20.2	26.3	7.2	17.1	16.1	4.5
CO2	Vol. %	27.9	23.0	37.9	11.3	11.1	20.9
H2/CO	mol/mol	2.2	1.7	6.4	1.3	1.2	6.7
HHV	MJ/m3	8.63	9.25	7.02	5.19	4.43	5.79

Continued.....

SUMMARY OF RESULTS

HIGHVALE COAL

Run No		83.1	83.2	83.3	83.4	85	86
OPERATING CONDITIONS							
Pressure	Atm.	9.64	8.38	7.67	9.78	9.13	8.94
Temp	C	650	655	682	699	755	780
Coal feed	kgMAF/hr	5.12	5.12	5.12	5.12	4.64	3.32
H2O/MAF	kg/kg	3.70	3.70	2.69	2.69	2.90	4.50
Air/MAF	kg/kg	1.22	1.92	2.56	2.27	3.48	4.93
N2/MAF	kg/kg	1.31	1.86	2.30	2.08	3.06	4.36
O2/MAF	kg/kg	0.29	0.45	0.60	0.53	0.82	1.16
RESULTS							
C Conv.	Wt. %	40.8	53.4	66.0	81.8	94.0	129.9
Effic.	%	34.1	44.4	57.8	79.3	78.9	108.7
H2O Decom	kg/kgMAF	0.33	0.42	0.52	0.65	0.64	0.90
H2O Decom	Wt. %	8.8	11.3	19.3	24.2	22.1	20.0
DRY GAS ANALYSIS							
H2	Vol. %	23.6	24.6	25.1	28.9	25.2	23.9
N2	Vol. %	48.8	47.2	45.3	38.8	45.7	47.4
CH4	Vol. %	2.9	2.5	3.0	2.6	1.4	2.1
CO	Vol. %	4.5	5.4	7.3	13.5	10.3	8.8
CO2	Vol. %	20.1	20.1	19.1	16.0	17.3	17.8
C2H6	Vol. %	0.15	0.14	0.18	0.20	0	0.07
HHV	MJ/m3	4.84	4.92	5.45	6.58	5.10	5.04
Gas yield	m3/kgMAF	2.04	2.62	3.08	3.50	4.49	6.25
H2/CO	mol/mol	5.2	4.5	3.4	2.1	2.5	2.7
WET GAS ANALYSIS							
H2O	Vol. %	67.3	61.0	46.8	42.1	38.5	41.8
EQUILIBRIUM MODEL RESULTS (DRY GAS)							
H2	Vol. %	32.3	32.2	32.3	34.7	29.7	29.7
N2	Vol. %	43.3	42.5	41.1	35.7	42.9	43.8
CH4	Vol. %	0.18	0.27	0.64	1.61	0.25	0.10
CO	Vol. %	2.1	2.8	5.4	7.6	8.2	7.8
CO2	Vol. %	22.1	22.2	20.6	20.4	18.9	18.6
H2/CO	mol/mol	15.4	11.4	6.0	4.6	3.6	3.8
HHV	MJ/m3	4.46	4.57	5.05	6.03	4.92	4.82

Continued

TABLE 3

SUMMARY OF RESULTS

HIGHVALE COAL

Run No		87	88	89	91	KRW 1	KRW 2
OPERATING CONDITIONS							
Pressure	Atm.	9.28	8.35	14.44	8.11	14.61	14.61
Temp	C	709	704	747	815	903	928
Coal feed	kgMAF/hr	5.16	6.05	5.72	4.39	228.4	236.1
H2O/MAF	kg/kg	2.56	1.64	4.50	1.34	1.41	1.35
Air/MAF	kg/kg	3.09	2.87	2.96	4.16	4.42	4.81
N2/MAF	kg/kg	2.75	2.50	2.58	4.25	4.40	4.71
O2/MAF	kg/kg	0.72	0.67	0.69	0.98	1.04	1.13
RESULTS							
C Conv.	Wt. %	91.4	84.1	103.1	100.3	81.0	91.0
Effic.	%	78.2	73.7	92.4	88.9	66.1	72.8
H2O Decom	kg/kgMAF	0.66	0.54	0.84	0.61	0.32	0.30
H2O Decom	Wt. %	25.7	32.8	18.6	45.2	22.4	22.5
DRY GAS ANALYSIS							
H2	Vol. %	25.2	23.7	26.7	19.0	13.1	12.7
N2	Vol. %	43.6	44.6	43.0	56.0	62.5	62.5
CH4	Vol. %	2.9	2.8	3.0	1.7	1.3	1.1
CO	Vol. %	8.9	12.7	7.9	12.0	9.5	10.8
CO2	Vol. %	19.2	16.1	19.3	11.3	13.5	12.9
C2H6	Vol. %	0.15	0.14	0.18	0.02	0	0
HHV	MJ/m3	5.60	5.83	5.72	4.63	3.95	3.95
Gas yield	m3/kgMAF	4.05	3.66	4.68	5.56	5.42	5.91
H2/CO	mol/mol	2.8	1.9	3.4	1.6	1.4	1.2
WET GAS ANALYSIS							
H2O	Vol. %	36.9	27.2	49.3	14.1	20.1	18.1
EQUILIBRIUM MODEL RESULTS (DRY GAS)							
H2	Vol. %	30.4	25.0	33.9	21.8	15.9	15.0
N2	Vol. %	40.7	43.9	38.9	54.1	60.6	60.9
CH4	Vol. %	1.05	0.93	0.42	0.20	0.02	0.01
CO	Vol. %	8.0	8.9	6.5	14.0	11.0	12.1
CO2	Vol. %	19.9	21.2	20.4	9.9	12.5	12.0
H2/CO	mol/mol	3.8	2.8	5.2	1.6	1.4	1.2
HHV	MJ/m3	5.31	4.69	5.31	4.63	3.42	3.45

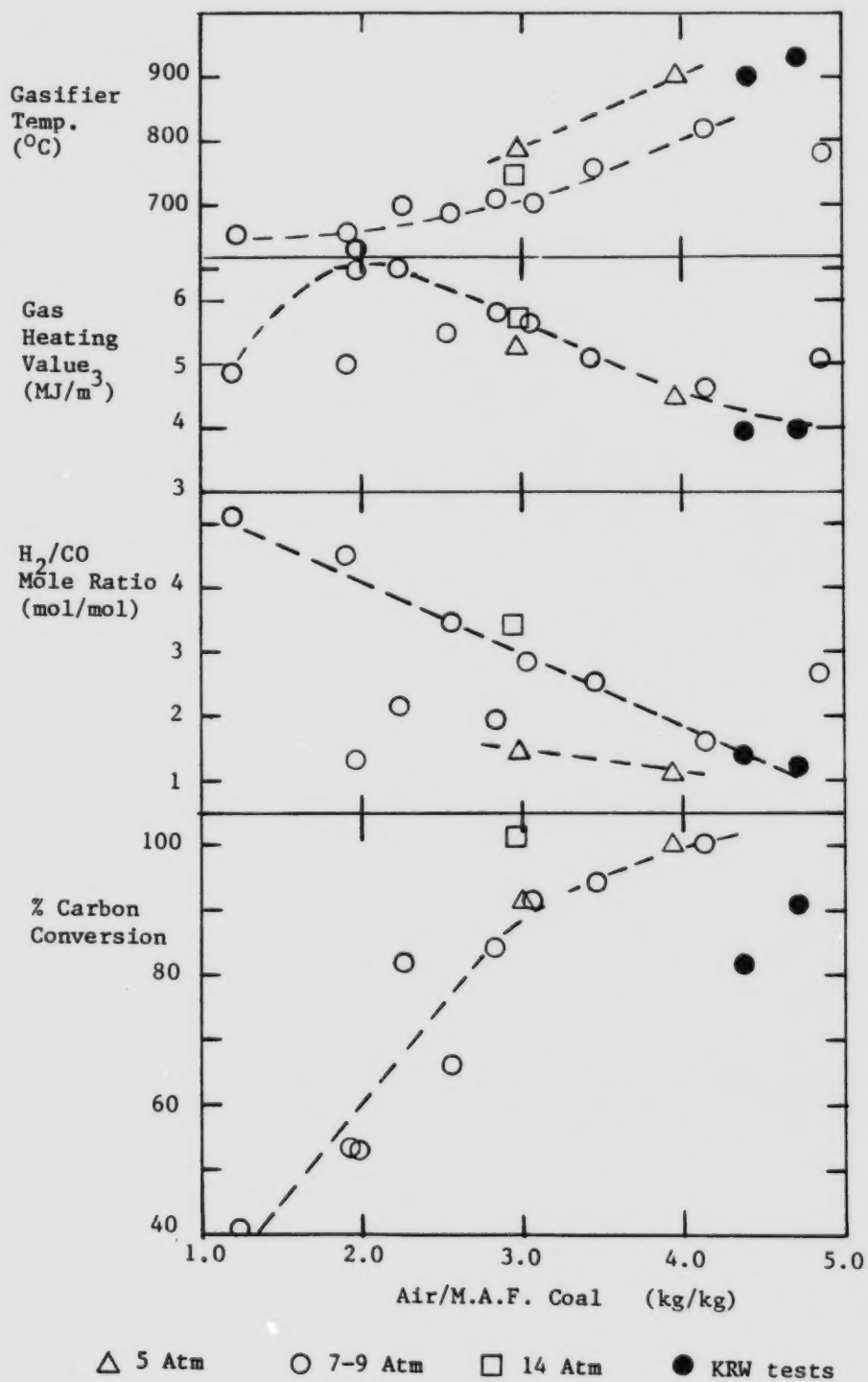


FIGURE 3 Plot of Performance Characteristics versus Air/Coal Ratio for Highvale Coal.

air/coal ratio increases, the dry gas heating value drops off as one begins to approach combustion conditions (for stoichiometric combustion of Highvale coal, air/coal = 10.7). On the other hand at low air/coal ratios, insufficient oxygen and hence combustion heat will decrease the reactor temperature and ultimately quench all reactions. Thus the air/coal ratio or oxygen/coal ratio is a useful parameter against which to plot primary results. It should be noted that the total throughput as well as the ratio of air/coal is important, as a given gasifier can process only a limited amount of coal at a given air/coal ratio. Thus in making comparisons at given air/coal ratios the magnitude of each flow should also be kept in mind. Examination of Figure 3 reveals the following:

1. Increasing the air/coal ratio from 1.8 to 4 results in a steady increase in temperature from 660°C to 800°C. At an air/coal ratios between 3.8 and 5 the temperature is almost constant at $780 \pm 20^\circ\text{C}$. At lower pressures temperatures are higher for a fixed air/coal ratio.
2. As the air/coal ratio increases, the gas heating value decreases. As well the H_2/CO molar ratio in the gas drops from about 4.5 down to about 2. The highest gas heating value produced in air/steam blowing was about 6 MJ/m^3 . At air/coal ratios between 2.5 and 3.5 gas heating values in the range $5 - 5.7 \text{ MJ/m}^3$ were common.
3. Carbon conversion increases strongly with air/coal ratio, reaching 90% at air/coal = 3. It should be noted that high carbon conversion is only useful if the gas heating value remains over about 3.8 MJ/m^3 so that it can sustain combustion.

It is clear from Figure 3 that results of the air/coal ratio effect on gas heating value, H_2/CO molar ratio and percent carbon conversion could as

well be plotted versus gasifier temperature, which would show similar trends. However, since temperature is dictated primarily by the air/coal ratio, the plot of gasifier performance versus air/coal ratio seems preferable.

Figure 4 shows some additional process response factors plotted in the same way as in Figure 3.

The steam decomposition and the gas yield both show increasing values with air/coal ratio. Note that for the carbon/steam reaction 1 kgC decomposes 1.5 kg steam and that results are below 0.9 kg steam/kgC. The gas yield as defined includes the nitrogen in the incoming blast so the increase with air/coal ratio is not surprising.

It is evident that if the gas heating value decreases weakly with air/coal ratio, at air/coal ratios > 2 , and the gas yield increases strongly and steadily with air/coal ratio, that the cold gas efficiency should increase with the gas yield. This is shown in Figure 4. The plot suggests that the process should be operated at as high an air/coal ratio as is permitted with the bounds of producing a burnable gas.

Run 80 appears to give results that are not in agreement with the trends of most of the other data in Figures 3 and 4. The reason for this is not immediately apparent.

Highvale Coal: Oxygen Fired Runs

Three runs were undertaken to compare air and oxygen blown operation. For the oxygen blown runs the amount of steam was increased substantially to control the reactor temperature and provide the fluidizing/spouting gas. Some nitrogen was added to aid the coal flow and the resulting gases

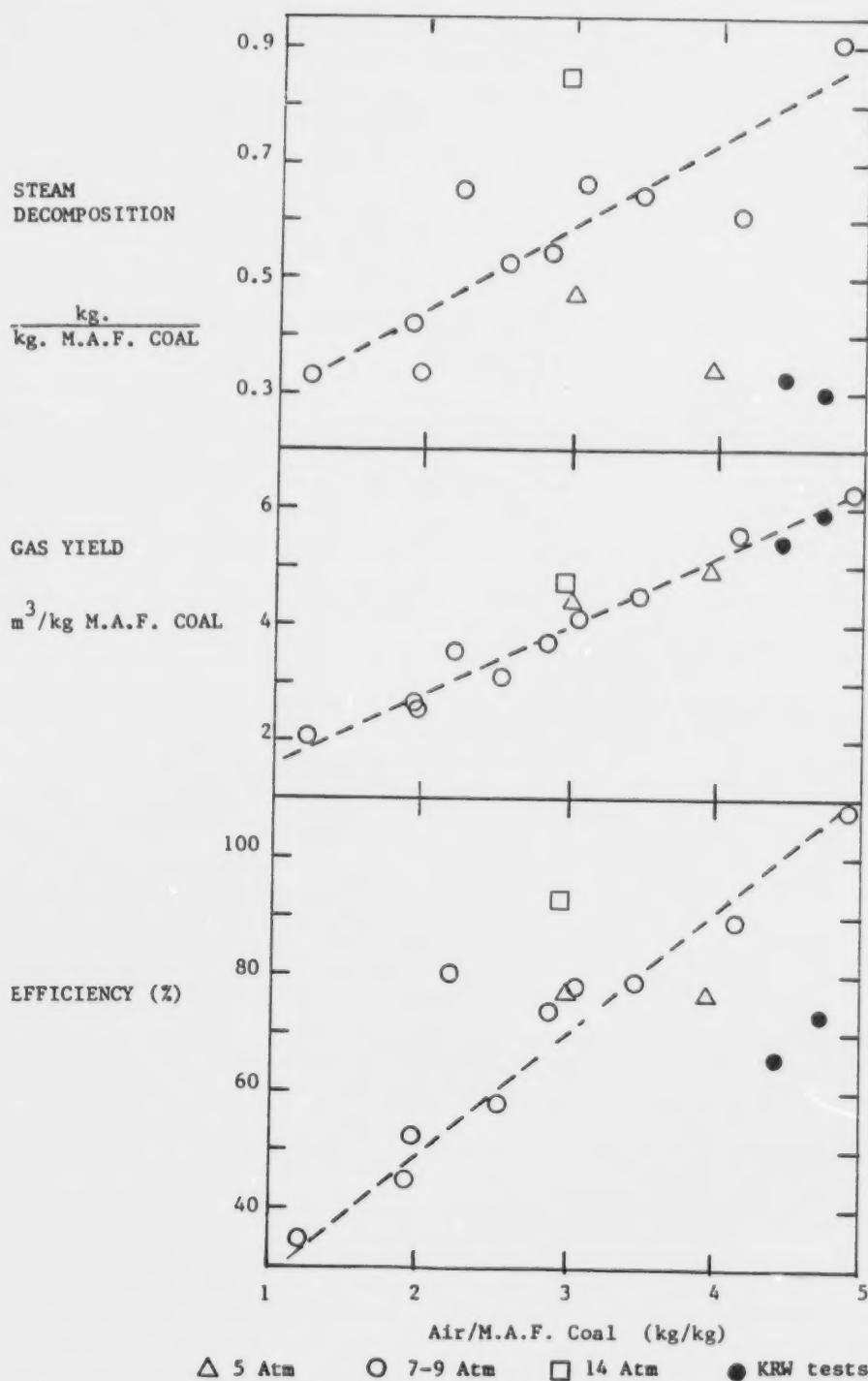


FIGURE 4 Plot of Performance Characteristics versus Air/Coal Ratio for Highvale Coal.

contained 5.5-9.3% vol. N_2 . Gas heating values in excess of 10 MJ/m^3 were produced in two of the oxygen/steam blown runs. Figures 5 and 6 shows air and oxygen blast runs compared directly by plotting performance parameters versus O_2 /coal rather than air/coal ratio. On such a basis, gasifier temperature is higher than for air blowing, a reflection of the lesser amount of total diluent (N_2 plus unreacted steam) available in the oxygen blown tests. The carbon conversion is therefore higher than in air blowing. Gas yield is lower as expected since there is little nitrogen in the blast.

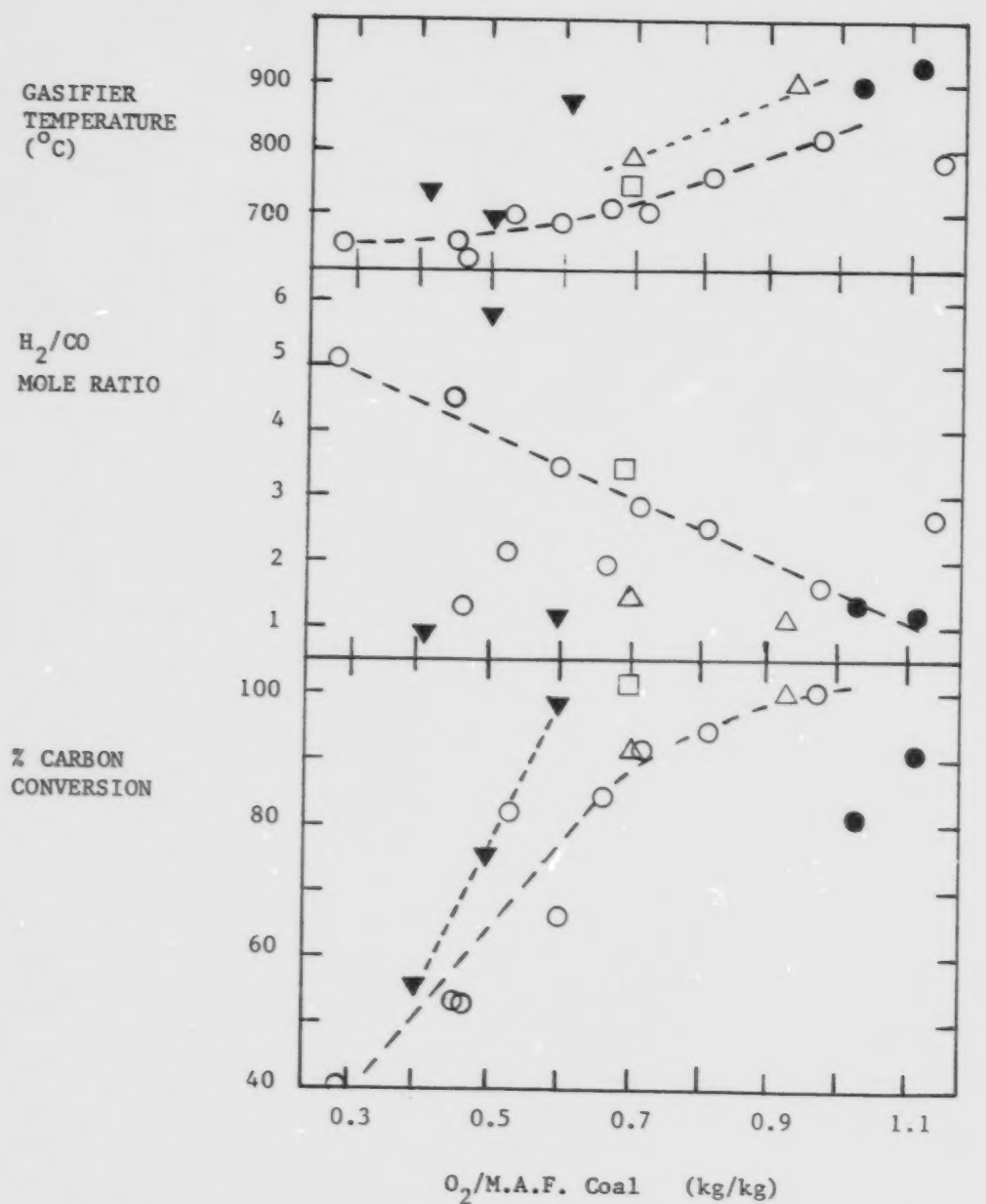
Figure 7 shows the diluent effect in which the gas heating value is plotted versus the N_2 /coal ratio. A relatively smooth curve covers the range giving heating values of about 10 MJ/m^3 down to 4 MJ/m^3 depending on the nitrogen diluent. This plot partially explains the lower heating values found for the KRW test data which was taken at larger inert gas/coal ratios than in the current experimental program.

Highvale Coal: Effect of Steam Rate

The effects of steam rate or steam partial pressure were not obvious in the results. Plots of carbon conversion, and steam decomposition/carbon conversion versus either steam rate or steam partial pressure gave only widely scattered results. The percentage steam decomposition was found to decrease as the steam partial pressure increased, which was not a surprising result. Additional observations are given below under pressure effects.

Highvale Coal: Effect of Total Pressure

Figures 3 and 4 have already shown effects of total pressure on some gasification parameters. At constant air/coal ratios higher pressures give



O₂ blown:

Air blown:

Δ 5 Atm ∇ 7-9 Atm $\square$ 14 Atm $\bullet$ KRW tests

FIGURE 5 Plot of Performance Characteristics versus Oxygen Ratio for Highvale Coal.

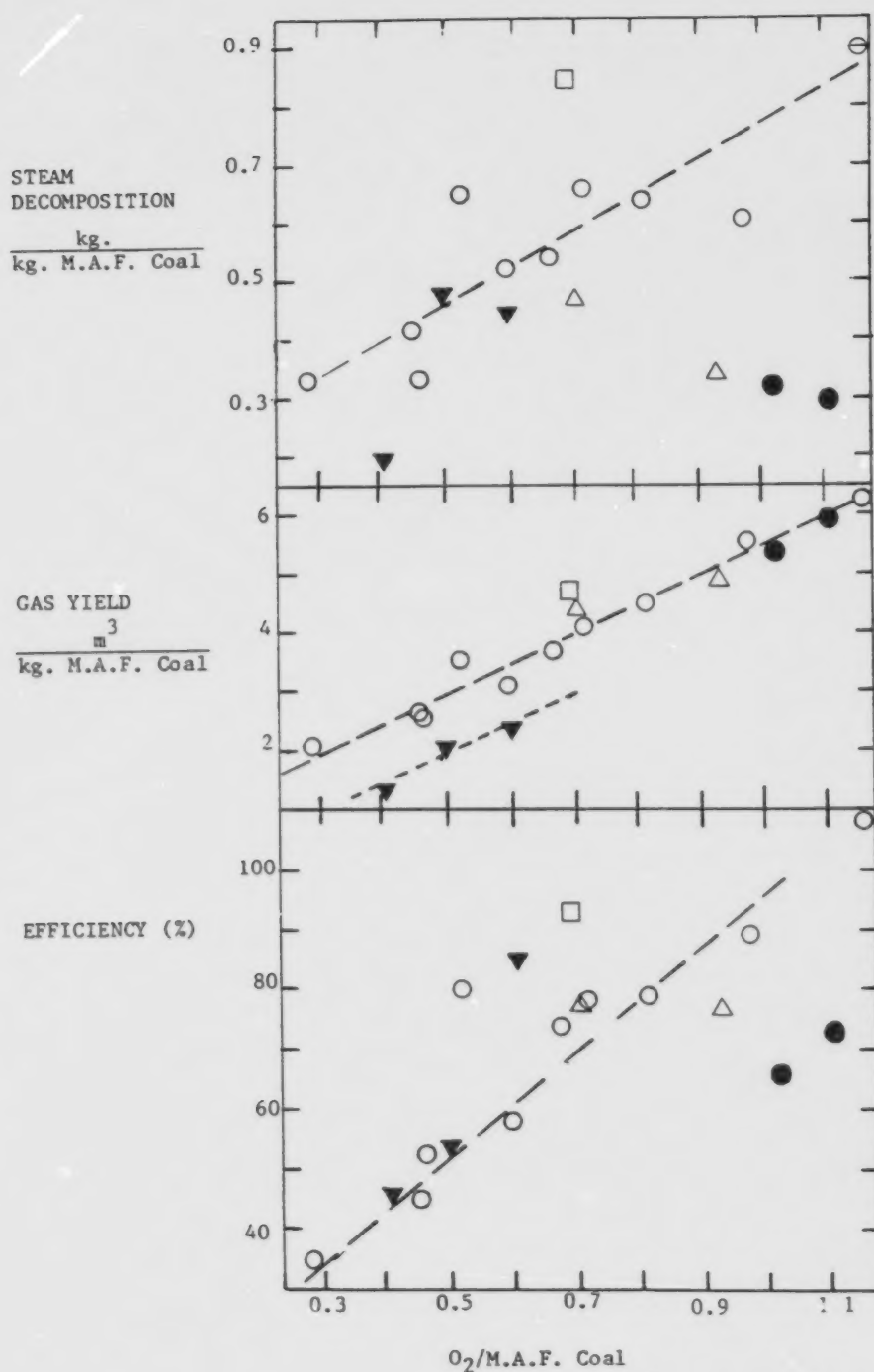


FIGURE 6 Plot of Performance Characteristics versus Oxygen Ratio for Highvale Coal.

TABLE 4 Effect of Total Pressure - Highvale Coal

Pressure (atm)	5.2	9.3	14.4
Temperature °C	789	747	747
Air/Coal Ratio (kg/kg)	3.01	2.87	2.96
H ₂ O/Coal Ratio (kg/kg)	0.96	1.64	4.50
Gas Heating Value (MJ/m ³)	5.25	5.83	5.72
Gas Yield (m ³ /kg)	4.22	3.66	4.68
H ₂ /CO Ratio (mol/mol)	1.4	1.9	3.4
% Carbon conversion	90.4	100	100
% Efficiency	76.5	92.4	88.9
Run No.	75.1	88	89

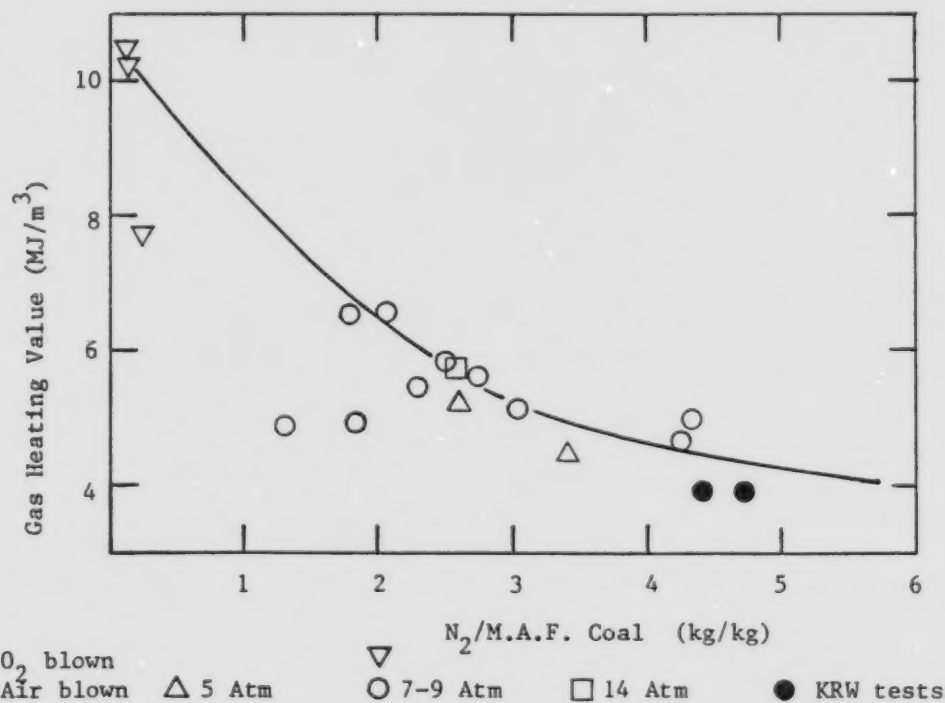
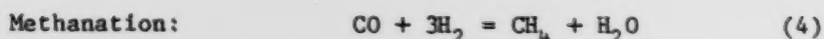
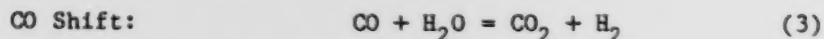
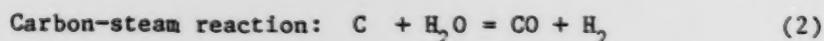
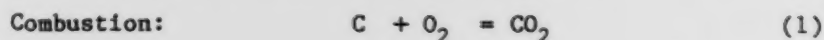


FIGURE 7 Effect of N₂/Coal Ratio on Gas Heating Value for Highvale Coal

lower temperatures, slightly higher gas heating values, and higher H_2/CO ratios. Table 4 shows data from three runs compared. It is seen that there is little change in the gasification performance parameters between 10 and 14.4 atm total pressure. Steam decomposition does increase with total pressure, and carbon conversion appears to be higher at 14.4 atm than at 5 or 9 atm. Lower H_2/CO molar ratios were produced at 5 atm than at 9 or 14.4 atm.

Highvale Coal: Product Gas Composition

The reactions describing the gasification process are:



Although, in practice, there may be additional reactions taking place, they can be considered as combinations of the above reactions. Plots of gas composition versus a single variable such as temperature, or air/coal ratio tend to give scattered results as other variables are not readily held constant while the parameter in question is changed. Nevertheless certain general effects can be noted: As temperature increases, CO_2 content declines while CO content increases. H_2 tends to go through a maximum at about 750°C in line with observations on steam decomposition.

Figures 8a to 8c show the calculated equilibrium gas species concentrations versus experimental value for CO, CO_2 and H_2 . In Figure 8a the CO concentration is shown to be well predicted, except for three experimental points. The CO_2 concentration (Figure 8b) shows slightly more

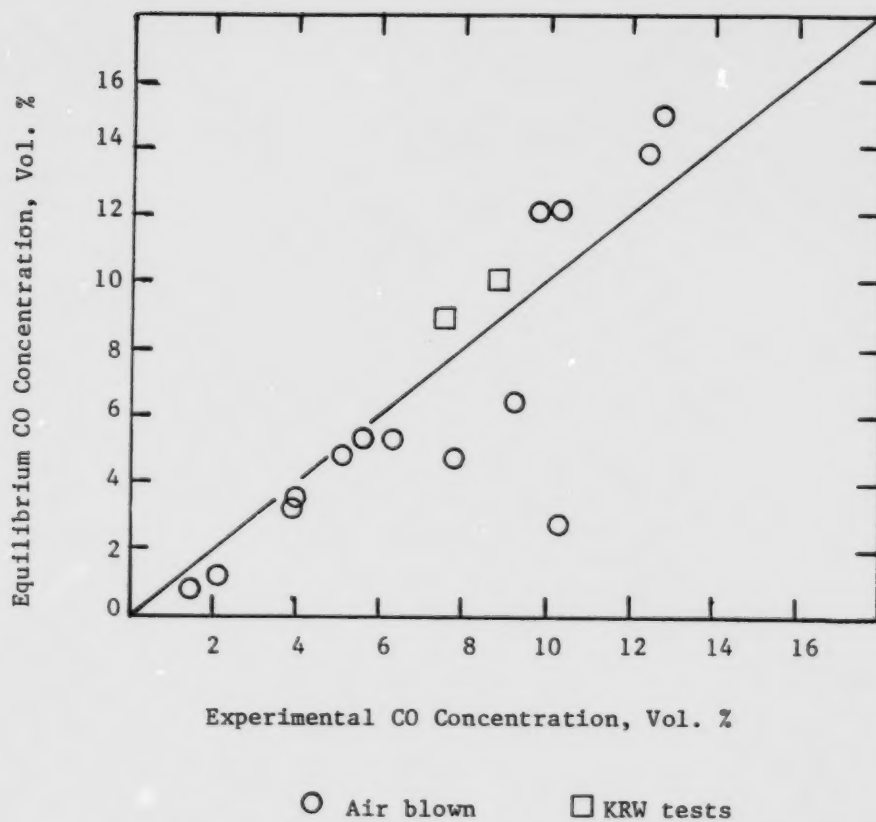


FIGURE 8 Comparison of Calculated and Measured Dry Gas Composition for Highvale Coal.

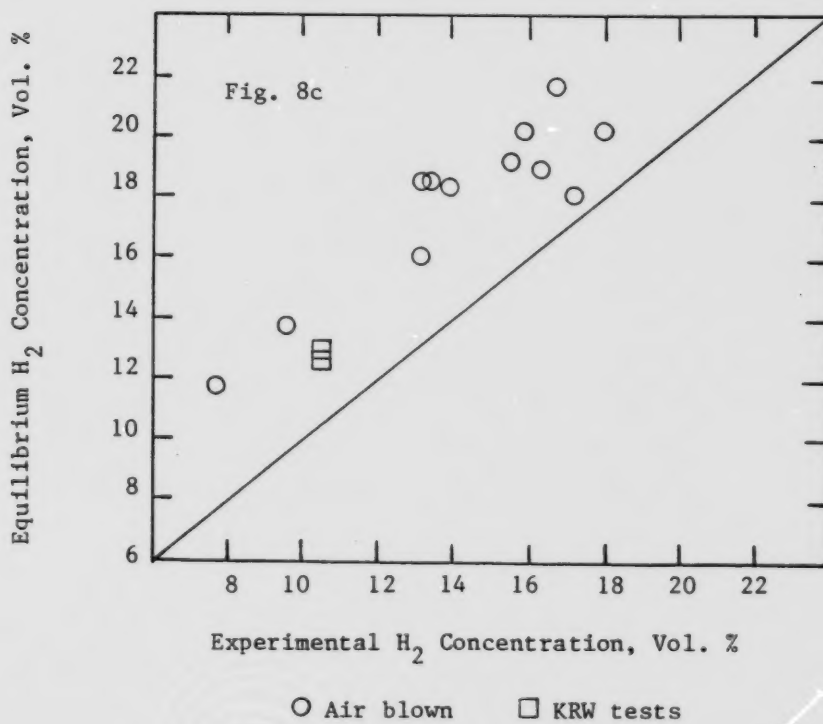
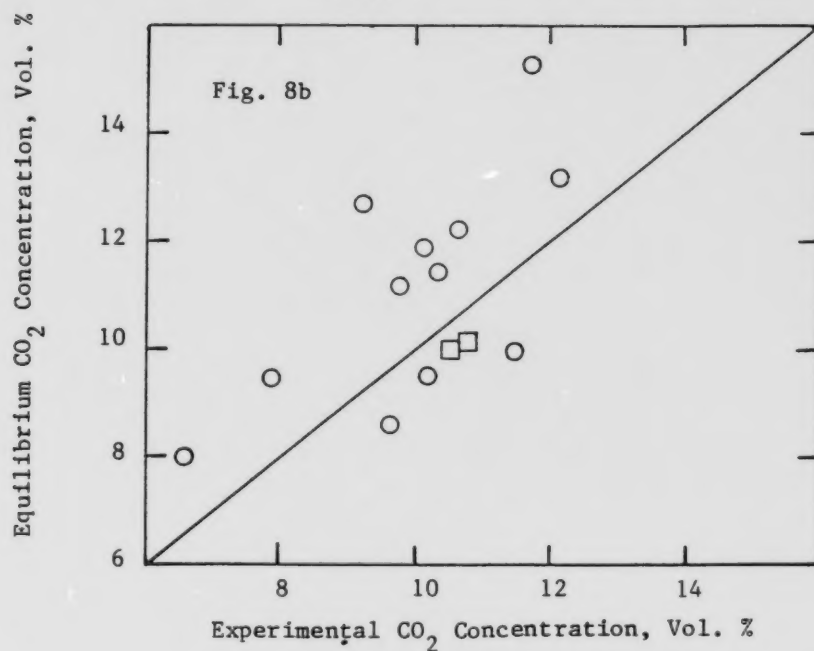


FIGURE 8 Comparison of Calculated and Measured Dry Gas Composition for Highvale Coal.

scatter, with nearly all points are within $\pm 15\%$. For the hydrogen (Figure 8c) however, the experimental H_2 values are all below the level predicted by the model. The model predicts H_2 values about 1.3 times the values measured. Nevertheless the trends are well predicted. As the H_2 increases from 8% to 17%, the model predicts an increase from 11% to 20%. This behaviour, coupled with that shown in Figure 8a and 8b lends confidence to the model predictions as a guide to plant performance, however a H_2 correction should be applied. The data for the KRW air-blown tests fits as well to the model as does the experimental data, with a similar error in direction from equilibrium in H_2 content.

Highvale Coal: Comparison with KRW Tests

Data from the KRW tests⁽⁶⁾ on Highvale Coal which were carried out at about 40 times the throughput of the present experimental runs are plotted in Figures 3, 4, 7 and 8. Gasifier temperature was higher in the KRW tests, whereas carbon conversion, steam decomposition and cold gas efficiency were considerably lower in the KRW tests. Gas yield, H_2/CO molar ratio and gas heating value were comparable in both units. The difference in heating value is largely explainable via Figure 7, and the agreement of the gas composition data in Figure 8a-c suggests that the bench scale unit is a good indicator of large scale performance. Among differences other than scale of operation, the KRW test was operated in a limestone bed, and used some gas recycle.

Highvale Coal: Gasification Process Considerations

The results have shown that Highvale coal is very reactive and that high carbon conversions can be obtained at relatively moderate temperatures and pressures. The product gas at temperatures above about 700°C is in chemical equilibrium and the equilibrium constraints limit the type of gas that could be obtained at higher temperatures. These considerations suggest that a fluidized or spouted bed reactor would be well suited to gasifying this coal. In contrast, a high temperature gasifier, operating close to or above the ash softening point would require relatively more energy input to achieve the same level of conversion. The gasification efficiency for the fluid/spouting bed gasifier would be higher, especially if the gasifier operates at conditions resulting in steam decomposition close to the maximum value.

A comparison of the results of gasification of Highvale coal and those of the other coals and specific conclusions drawn are given in the final section of this report.

Highvale Coal: Summary

Twelve successful experimental runs were carried out with Highvale coal, with some runs being done at several operating conditions. Coal was fed into the top of the bed at feed rates which averaged about 5 kg M.A.F. coal/h. Most tests were done at about 7-9 atm pressure, and a few trials at higher (14 atm) and lower (5 atm) pressure were completed. At air/coal ratios > 2 where gas heating value was 6.5 MJ/m^3 , a linear decrease in heating value with air/coal ratio was observed, reaching 4.5 MJ/m^3 at air/coal = 4. The H_2/CO molar ratio decreased with increasing air/coal

ratio in a similar manner. Temperature, carbon conversions, gas yield, steam decomposition and efficiency all increased linearly with air/coal ratio. In oxygen/steam gasification, heating values of 10 MJ/m^3 were achieved. Pressure had little effect. Gases were in equilibrium, except for H_2 which was about 30% below equilibrium concentration. Comparison of results with those of the KRW gasifier showed explainable differences in heating value, with the KRW unit producing weaker gas by virtue of the recycling of nitrogen rich gas to the unit.

No mechanical problems were evident in operating the gasifier on Highvale coal.

Coal Valley Coal: Introduction

The composition of the Coal Valley coal sample tested in this work is given in Table 2. Compared to the Highvale sample, it is higher in fixed carbon (61.3 vs. 42.8% M.A.F. basis) and lower in volatile matter (38.8 vs. 57.2% M.A.F. basis). It is a bituminous coal, and thus one would expect it to be somewhat lower in reactivity, thus requiring more severe conditions and lower throughputs to gasify to the same extent of carbon conversion. In presenting the results, plots which correspond to those given above for Highvale coal are used so that direct comparisons between the two coals can be made. The dashed lines drawn by eye through the Highvale coal data of Figures 3 and 4 are reproduced on the corresponding figures for Coal Valley coal. Table 5 summarizes the data on Coal Valley coal.

Coal Valley Coal: Effect of Air/Coal Ratio

Figures 9 and 10 shown gasifier performance parameters plotted versus air/coal ratio. Coal feed rates on an M.A.F. basis were in the range 3.73 to 6.11 kg/h. For the Coal Valley coal, temperatures were roughly constant at 790 - 840°C except for oxygen blown runs. As the air/coal ratio was increased the gas heating value decreased in a manner similar to that of the Highvale coal, however the magnitudes of the values are less. H_2/CO ratios were somewhat scattered in the range 1.4 to 3.7 with what could be a slight maximum at an air/coal ratio of 3.7. Data are in rough agreement with the Highvale data line. Carbon conversion increased in essentially a linear manner with air/coal ratio; the highest value attained in the air blast runs was 84%. Steam decomposition was independent of air/coal ratio at 0.42 - 0.45 kg steam/kg carbon, although there is the hint of a slight maximum.

TABLE 5

SUMMARY OF RESULTS

COAL VALLEY

Run No		92	93	94	95	96
OPERATING CONDITIONS						
Pressure	Atm.	8.89	9.33	9.02	9.33	8.89
Temp	C	781	787	839	812	818
Coal feed	kgMAF/hr	6.11	4.62	5.13	3.73	4.20
H2O/MAF	kg/kg	1.87	4.93	1.87	2.31	3.83
Air/MAF	kg/kg	2.03	3.66	3.35	4.48	3.78
N2/MAF	kg/kg	1.85	3.18	2.91	3.89	3.35
O2/MAF	kg/kg	0.48	0.86	0.79	1.05	0.89
RESULTS						
C Conv	Wt. %	53.8	63.0	69.7	84.2	76.7
Effic	%	45.5	45.0	57.7	60.7	55.5
H2O Decom	kg/kgMAF	0.37	0.40	0.45	0.34	0.45
H2O Decom	Wt. %	20.0	8.1	24.1	14.9	11.8
DRY GAS ANALYSIS						
H2	Vol. %	21.8	15.4	17.7	13.9	16.4
N2	Vol. %	47.8	62.5	55.8	60.6	57.0
CH4	Vol. %	3.0	1.9	2.8	1.7	2.9
CO	Vol. %	10.1	4.1	9.1	10.6	5.7
CO2	Vol. %	17.0	15.9	14.5	13.0	17.8
C2H6	Vol. %	0.21	0.09	0.18	0.06	0.12
HHV	MJ/m3	5.42	3.32	4.63	3.86	4.05
Gas Yield	m3/kgMAF	2.60	4.20	3.86	4.87	4.25
H2/CO	mol/mol	2.2	3.8	2.0	1.3	2.9
WET GAS ANALYSIS						
H2O	Vol. %	41.7	57.3	31.4	33.5	49.8
EQUILIBRIUM MODEL RESULTS (DRY GAS)						
H2	Vol. %	25.0	22.2	24.7	16.6	24.9
N2	Vol. %	46.0	57.6	51.2	58.8	51.4
CH4	Vol. %	0.07	0.00	0.04	0.04	0.01
CO	Vol. %	6.8	2.9	9.8	6.0	5.4
CO2	Vol. %	22.2	17.3	14.2	18.6	18.3
H2/CO	mol/mol	3.7	7.6	2.5	2.8	4.6
HHV	MJ/m3	4.07	3.20	4.41	2.89	3.86

Continued.....

TABLE 5

SUMMARY OF RESULTS

COAL VALLEY

Run No		97	98	99	100	101
OPERATING CONDITIONS						
Pressure	Atm.	14.20	5.18	8.96	8.99	8.82
Temp	C	842	811	881	845	903
Coal feed	kgMAF/hr	5.81	6.48	4.68	5.36	5.48
H2O/MAF	kg/kg	4.68	1.79	5.68	4.50	4.49
Air/MAF	kg/kg	3.08	2.29	0	0	0
N2/MAF	kg/kg	2.65	2.03	0.41	0.42	0.44
O2/MAF	kg/kg	0.72	0.54	0.89	0.72	0.89
RESULTS						
C Conv	Wt. %	68.8	51.8	83.0	76.5	93.1
Effic	%	45.7	43.7	60.8	61.2	63.3
H2O Decom	kg/kgMAF	0.39	0.38	0.47	0.53	0.44
H2O Decom	Wt. %	8.3	21.4	8.3	11.8	9.8
DRY GAS ANALYSIS						
H2	Vol. %	18.3	17.8	34.8	33.7	32.0
N2	Vol. %	55.9	56.4	14.3	16.9	16.3
CH4	Vol. %	1.4	3.4	3.1	5.9	3.2
CO	Vol. %	5.3	6.6	15.2	12.0	15.7
CO2	Vol. %	19	15.6	32.1	31.3	32.1
C2H6	Vol. %	0.09	0.20	0.39	0.24	0.03
HHV	MJ/m3	3.62	4.59	7.89	8.32	7.38
Gas Yield	m3/kgMAF	3.92	2.94	2.39	2.28	2.65
H2/CO	mol/mol	3.4	2.7	2.3	2.8	2.0
WET GAS ANALYSIS						
H2O	Vol. %	57.7	37.4	73.1	68.4	65.5
EQUILIBRIUM MODEL RESULTS (DRY GAS)						
H2	Vol. %	23.3	26.2	44.8	46.6	41.1
N2	Vol. %	52.6	50.8	12.2	13.7	14.1
CH4	Vol. %	0.00	0.02	0.00	0.01	0.00
CO	Vol. %	4.1	7.9	8.5	9.4	11.4
CO2	Vol. %	20.1	15.1	34.5	30.4	33.4
H2/CO	mol/mol	5.7	3.3	5.3	5.0	3.6
HHV	MJ/m3	3.48	4.35	6.79	7.13	6.69

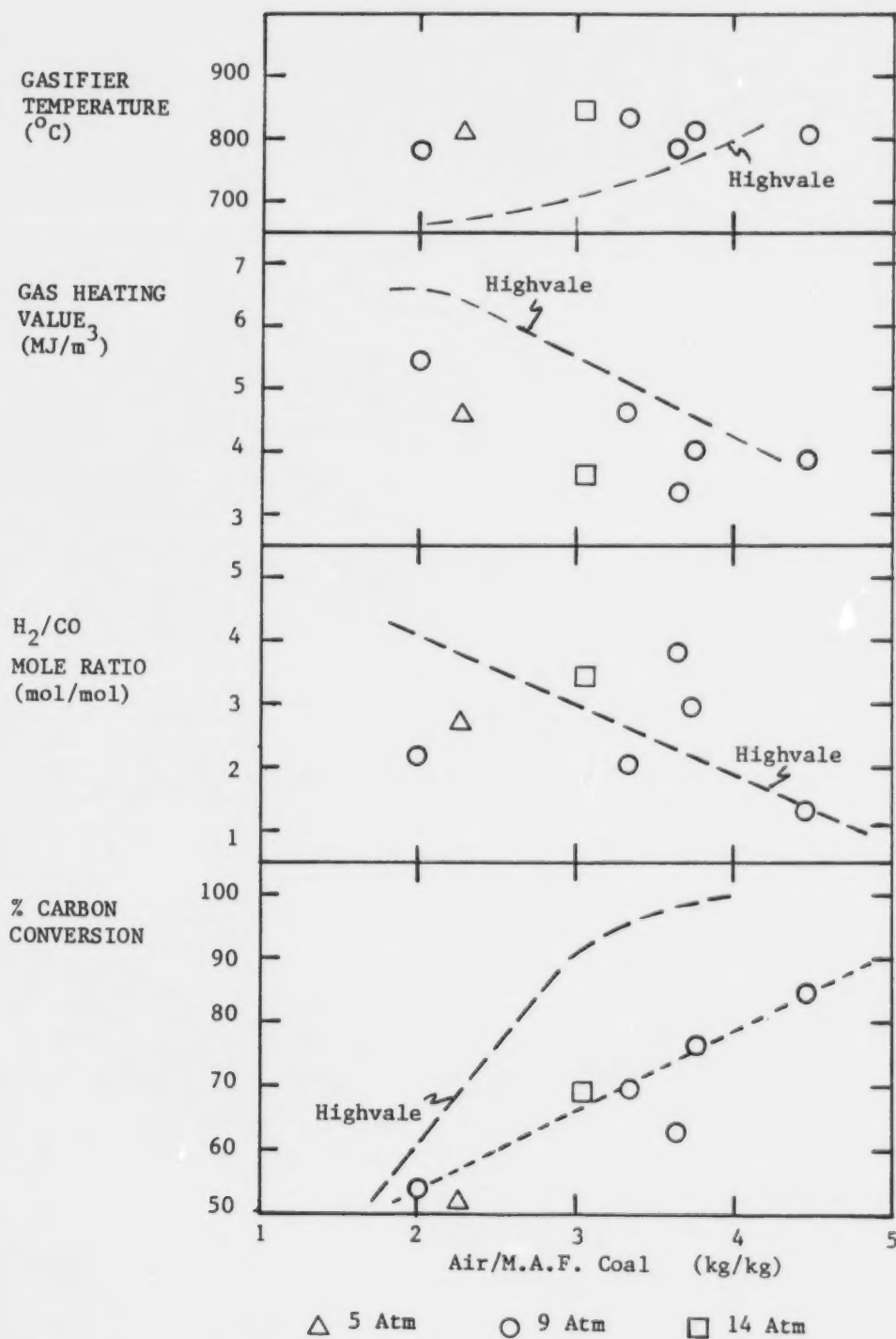


FIGURE 9 Plot of Performance Characteristics versus Air/Coal Ratio for Coal Valley Coal.

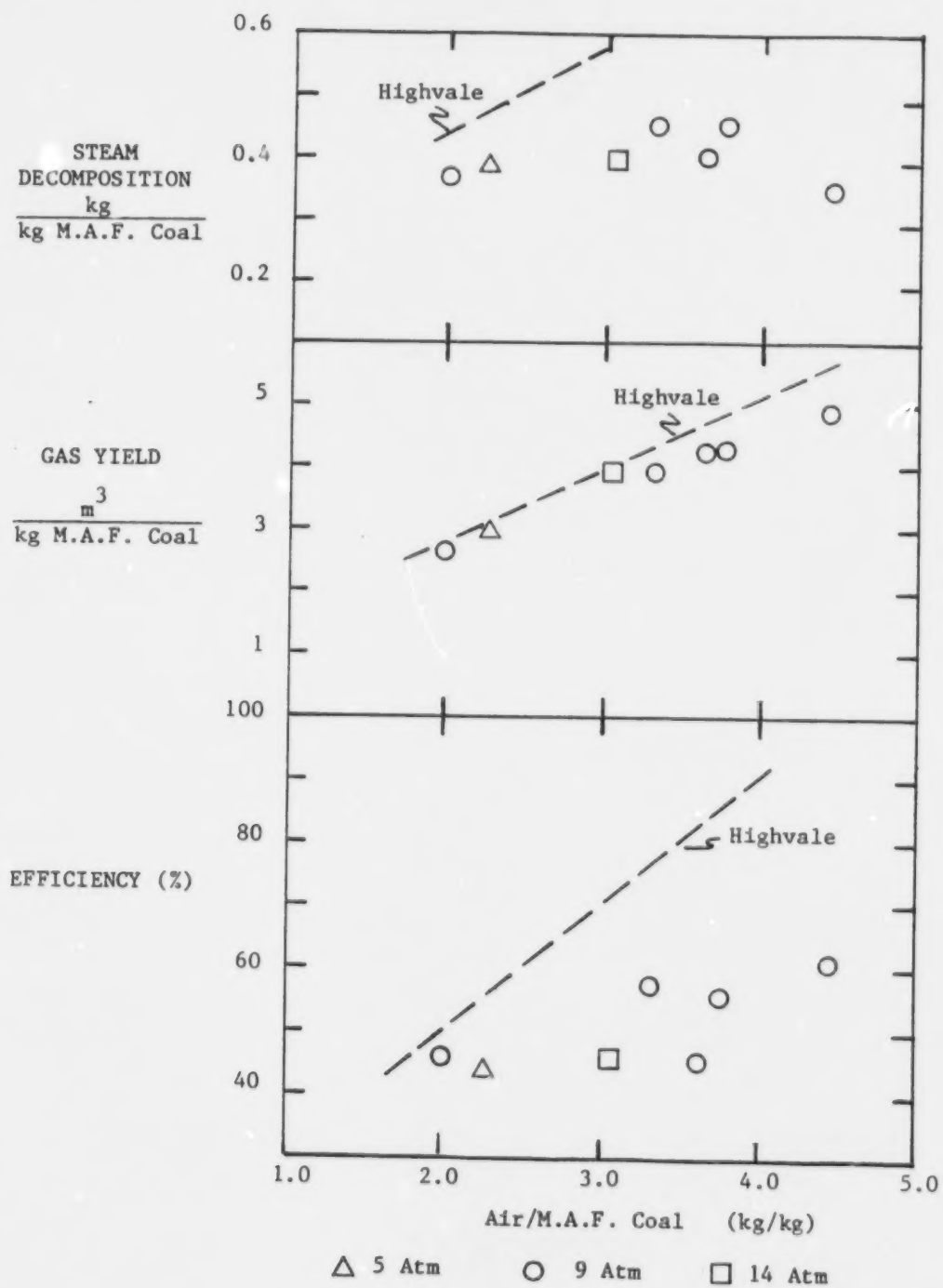


FIGURE 10 Plot of Performance Characteristics versus Air/Coal Ratio for Coal Valley Coal.

Gas yield increased in a linear manner with air/coal ratio as might be expected and in good agreement with the Highvale data. As in the case of Highvale coal, the gas heating value decrease with air/coal ratio is less than the gas yield increase with air/coal ratio, thus the cold gas efficiency rises with air/coal ratio. The efficiency values were markedly below those of Highvale coal and reached only about 60%.

Coal Valley Coal: Oxygen Fired Runs

Three runs were undertaken with oxygen/steam blasts rather than air/steam. Some nitrogen was still used to aid coal feeding so the gases ended up with about 15% N_2 , and gas heating values of 7.4 to 8.3 MJ/m³. Without this conveying N_2 , the achievable gas heating values would be 8.7 - 9.8 MJ/m³. Figures 11 and 12 shows the oxygen/steam blast runs compared to the air/steam runs by plotting performance versus O_2 /coal ratio. Compared to the air/steam runs the gasifier temperatures were about 100°C higher. H_2 /CO molar ratios are essentially the same as with air blowing. Carbon conversion is higher by a factor of 1.1 to 1.2 with oxygen blowing, this increase reflects the higher temperature of the latter runs. Values to 93% were achieved. Figure 13 shows a linear dependence of carbon conversion on temperature for the Coal Valley runs. Steam decomposition (Figure 12) is slightly higher than the air runs for the same reason. Gas yields are about 45% of the airblown runs because the non- O_2 content of the blast is higher for the air/steam runs. The cold gas efficiency values in oxygen/steam are slightly above those in the air/steam tests. Thus in general the oxygen fired runs are in basic agreement with the air fired runs.

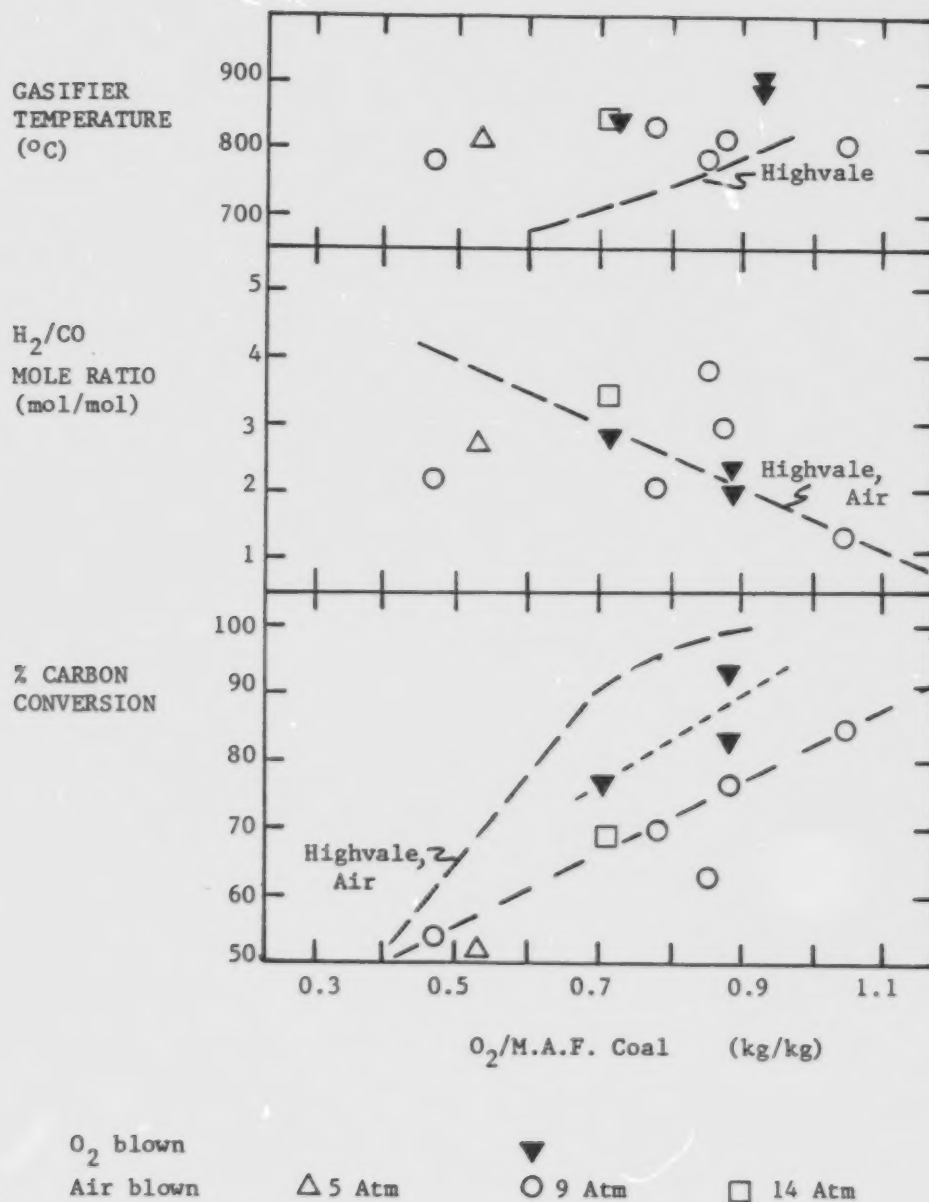


FIGURE 11 Plot of Performance Characteristics versus Oxygen/Coal Ratio for Coal Valley Coal.

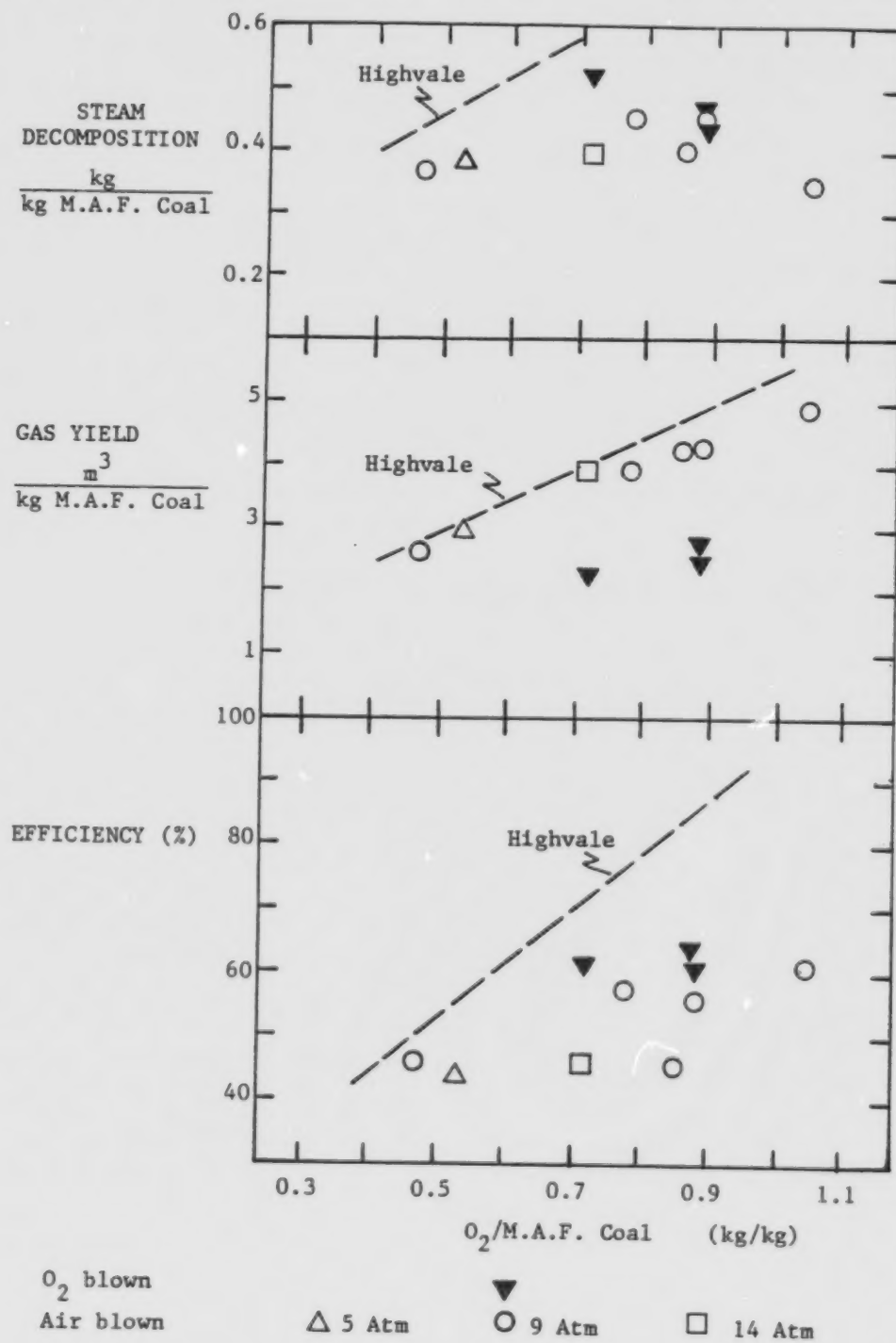


FIGURE 12 Plot of Performance Characteristics versus Oxygen/Coal Ratio for Coal Valley Coal.

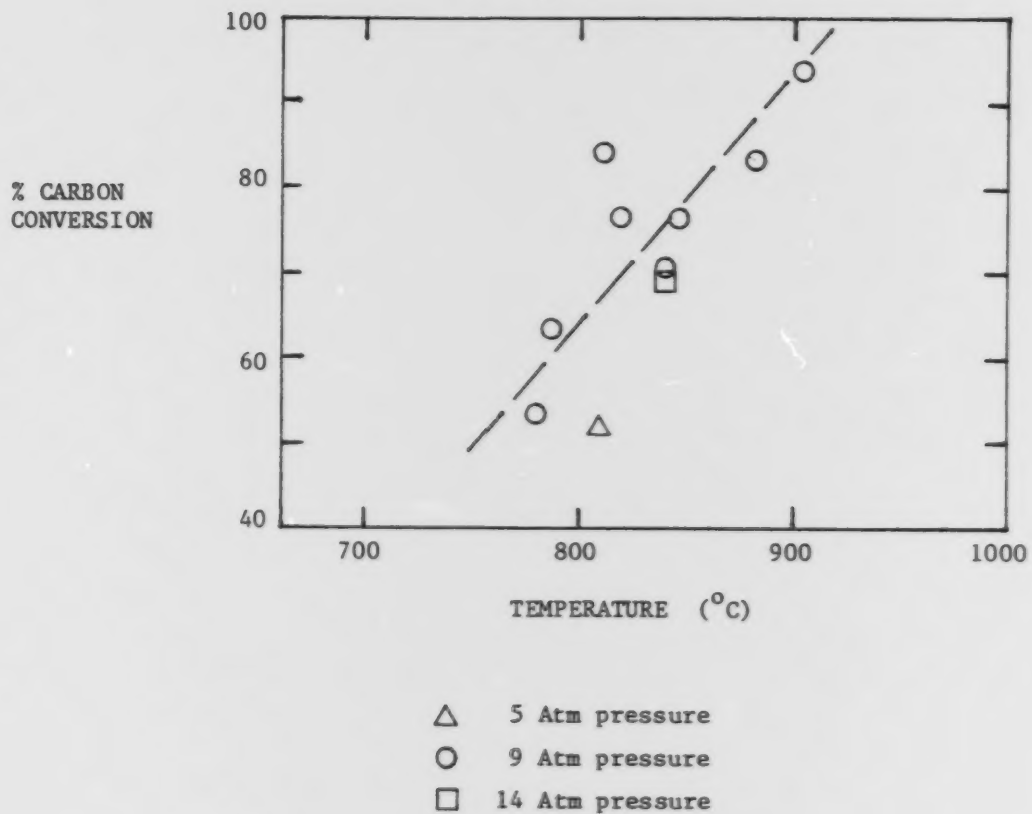


FIGURE 13 Carbon Conversion versus Gasifier Temperature for Coal Valley Coal.

Coal Valley: Effect of Pressure

Three pressure levels were tested 5, 9 and 14 atm. In Figures 9 and 10 the effect of total pressure is seen to be small. A slight effect on carbon conversion appears to exist with the low pressure (5 atm) run giving slightly lower carbon conversion and the high pressure (14 atm) run giving slightly higher carbon conversion than the bulk of the runs at around 9 atm pressure. The effect, however, is small. Detailed examination of the data suggests that increasing the partial pressure of steam increases the extent of steam decomposition at a given temperature. However, over the range tested, the pressure effect for the Coal Valley coal sample is very small.

Coal Valley: Product Gas Composition

As indicated in Figures 11 and 12, the O_2 /coal ratio is the key factor governing gas composition. As for the Highvale coal, comparisons are made of gas composition versus that predicted by equilibrium considerations. Figures 14a-c show the results. In common with the results of Figure 8, it is seen that CO levels are predicted fairly well by equilibrium considerations. The CO_2 levels are predicted quite well for five of the seven runs shown, but for two runs experimental values were markedly below theory. For H_2 , a similar result to Figure 8 is obtained once more - the experimental H_2 levels are about 70-80% of the values that equilibrium would predict.

Coal Valley Coal: Gasification Process Considerations

Coal Valley coal is less reactive than Highvale coal and more severe operating conditions would be required to achieve comparable carbon

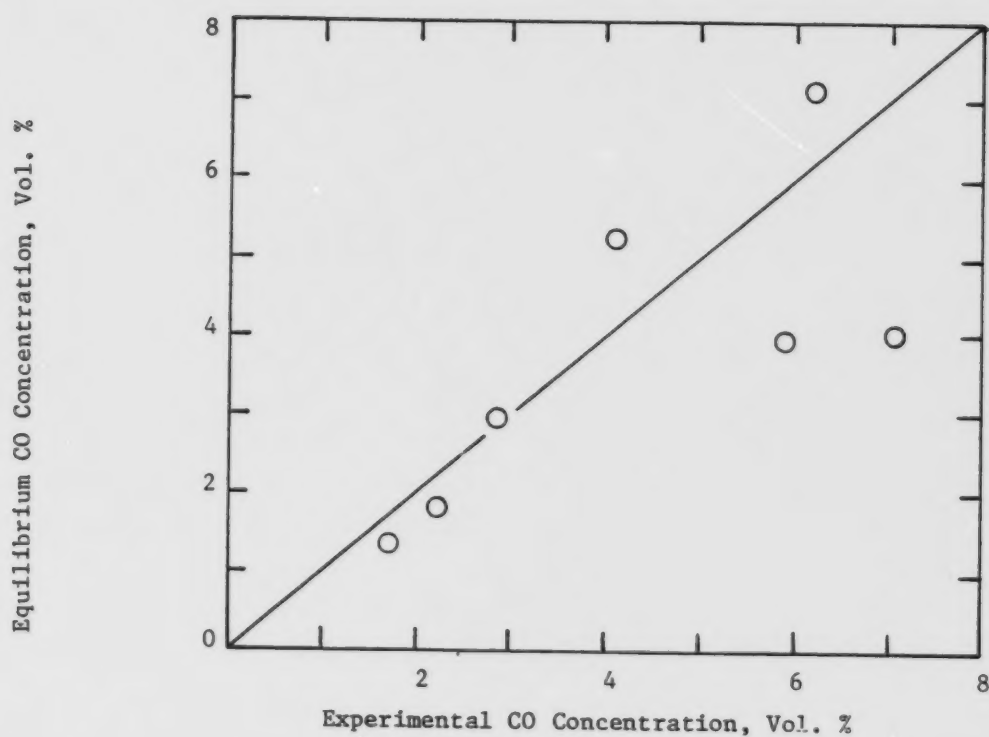


Fig. 14a

FIGURE 14 Comparison of Calculated and Measured Dry Gas Compositions for Coal Valley Coal.

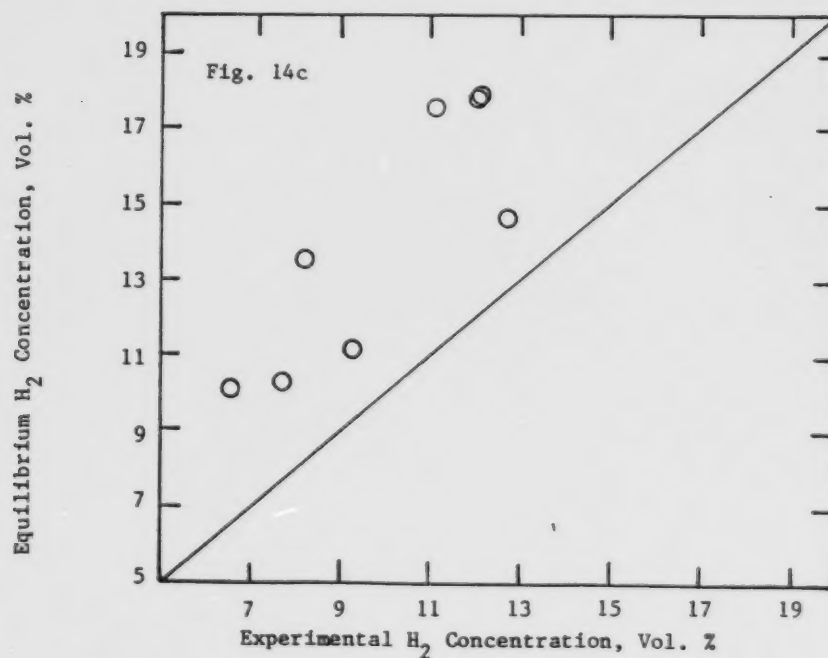
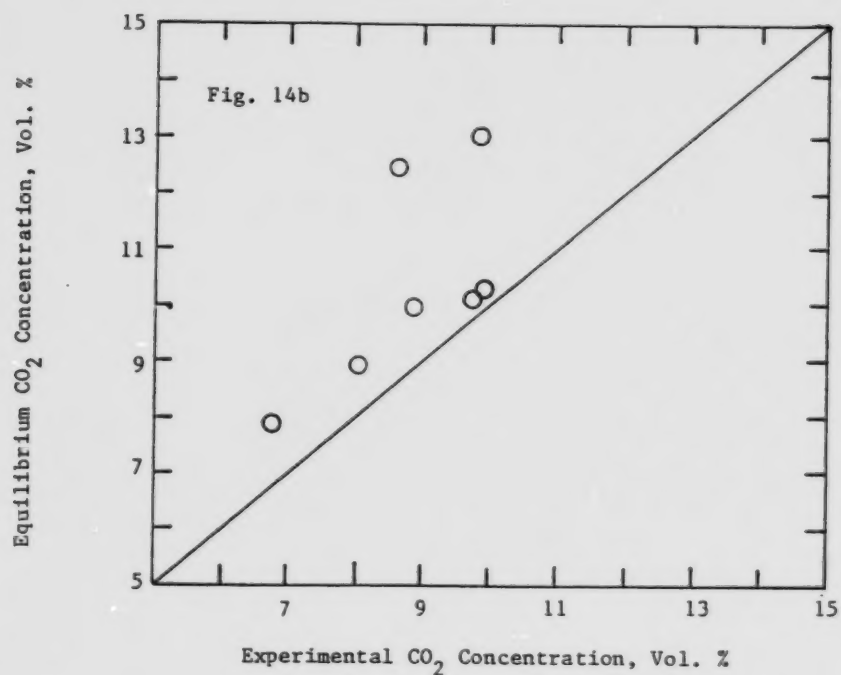


FIGURE 14 Comparison of Calculated and Measured Dry Gas Compositions for Coal Valley Coal.

conversion levels. Since pressure does not improve gasification, increasing the operating temperature would be the only feasible way to increase conversion. Over the range of temperatures studied the carbon conversion increases linearly with temperature and a temperature of about 900°C is required to achieve 90% carbon conversion. Fluid bed or spouted bed gasifiers would be capable of gasifying Coal Valley coal and operation at atmospheric pressure would be acceptable. Gasifiers operating at temperatures near or above the ash softening point would also be appropriate for this coal.

Coal Valley Coal: Summary

Ten successful experiments are reported for Coal Valley coal. Above bed feeding was used in these tests, and coal feed rates averaged about 5 kg M.A.F coal/h. Gasifier temperature was about 800°C, and pressure was held at 9 atm except for single runs at 5.2 atm and 14 atm. Gas heating value was 5.5 MJ/m³ at air/coal = 2, and decreased linearly to about 3.5 MJ/m³ at air/coal = 4. Three runs undertaken with oxygen steam firing gave gases of heating value 8.7 - 9.8 MJ/m³ on a N₂ - free basis. Pressure effects were small. Gases were low in H₂ compared to equilibrium model predictions.

No significant operating problems were noted with this bituminous coal. It is less reactive than the sub-bituminous coal tested, and thus required more severe conditions, and produced lower efficiencies.

Byron Creek Coal

The analysis of Byron Creek coal shown in Table 2 indicates that it is a bituminous coal with low volatile content (25%), and a fixed carbon content of about 61%. It is a weakly caking coal with a free swelling index of 4.5. Results of six experiments carried out on Byron Creek coal are shown in Table 6.

Byron Creek Coal: Effect of O_2 /Coal Ratio

Five tests were conducted with air blast and one using air enriched with oxygen. In general, increasing the oxygen/coal ratio increases the gasifier temperature because this induces a greater amount of coal combustion.

Figure 15 shows a series of gasification results plotted versus the oxygen/coal ratio. The gasifier temperature increases essentially linearly with the oxygen/coal ratio. As the oxygen/coal ratio increases, the dry gas heating value declines as combustion conditions are approached. Thus the production of good quality fuel gas is favored at low oxygen/coal ratios. However, at low oxygen/coal ratios the deficiency of oxygen causes a reduction in the level of combustion resulting in a decline in reactor temperature and quenching of the reactions. Thus the oxygen/coal ratio is a useful parameter against which to plot primary results. It should be noted that the total throughput as well as the ratio of oxygen/coal is important, as a given gasifier can process only a limited amount of coal at a given oxygen/coal ratio. Thus in making comparisons at given oxygen/coal ratios the magnitude of each flow should also be kept in mind. Comparison of Table 6 with Table 5 and Table 3 indicates that the gasifier was de-rated when

SUMMARY OF RESULTS

BYRON CREEK

Run No		148	149	151	152	153	161
OPERATING CONDITIONS							
Oxidant		Air	Air	Air	Air	Air	Air+O2
Pressure	Atm.	4.54	4.13	4.27	4.61	4.61	6.27
Temperature	C	839	813	828	839	852	899
Coal Rate	kg MAF/hr	2.73	3.25	3.41	3.87	4.08	2.76
Steam Rate	kg/hr	15.0	12.6	13.8	13.5	12.3	15.8
Air Rate	kg/hr	14.7	15.4	15.0	17.3	19.5	18.8
O2 Rate	kg/hr	3.46	3.60	3.53	4.06	4.59	5.19
Added N2	kg/hr	0.77	0.75	0.57	0.58	0.58	0.59
Sup. Vel.	m/sec	0.73	0.67	0.71	0.68	0.64	0.60
H2O/MAF	kg/kg	5.50	3.89	4.05	3.50	3.02	5.72
Air/MAF	kg/kg	5.40	4.72	4.41	4.47	4.80	6.80
O2/MAF	kg/kg	1.27	1.11	1.03	1.05	1.13	1.88
N2/MAF	kg/kg	4.41	3.85	3.54	3.57	3.81	5.42
RESULTS							
C Conv.	Wt. %	93.9	72.3	69.5	71.0	70.6	99.6
Efficiency	%	48.2	38.3	42.1	41.8	42.3	27.2
H2O Decomp.	kg/kg MAF	0	0	0.08	0.10	0.10	0
H2O Decomp.	Wt. %	0	0	1.9	2.8	3.3	0
DRY GAS ANALYSIS							
H2	Vol. %	5.9	6.0	7.9	8.8	8.4	3.0
N2	Vol. %	64.6	66.6	64.4	63.8	64.9	70.7
CH4	Vol. %	1.1	1.4	1.7	1.6	1.6	0.7
CO	Vol. %	16.4	14.4	15.1	13.8	13.6	7.3
CO2	Vol. %	11.9	11.5	10.8	12.0	11.4	18.3
C2H6	Vol. %	0	0	0.08	0	0.07	0
HHV	kcal/m3	785	753	872	835	834	373
HHV	MJ/m3	3.29	3.15	3.65	3.50	3.49	1.56
H2/CO	mol/mol	0.36	0.42	0.53	0.64	0.62	0.41
Gas Yield	m3/kg MAF	5.15	4.27	4.05	4.19	4.26	6.11
WET GAS ANALYSIS							
H2O	Vol. %	57.4	53.2	55.0	50.3	46.0	54.8
EQUILIBRIUM MODEL RESULTS (DRY GAS)							
H2	Vol. %	19.0	18.5	21.1	20.2	19.3	9.5
N2	Vol. %	55.6	57.8	55.3	55.9	57.2	66.0
CH4	Vol. %	0	0	0	0	0	0
CO	Vol. %	4.2	4.1	4.5	5.2	5.8	2.5
CO2	Vol. %	21.2	19.6	19.2	18.8	17.7	22.0
HHV	MJ/m3	2.95	2.88	3.26	3.23	3.20	1.53
H2/CO	mol/mol	4.55	4.53	4.71	3.91	3.33	3.78

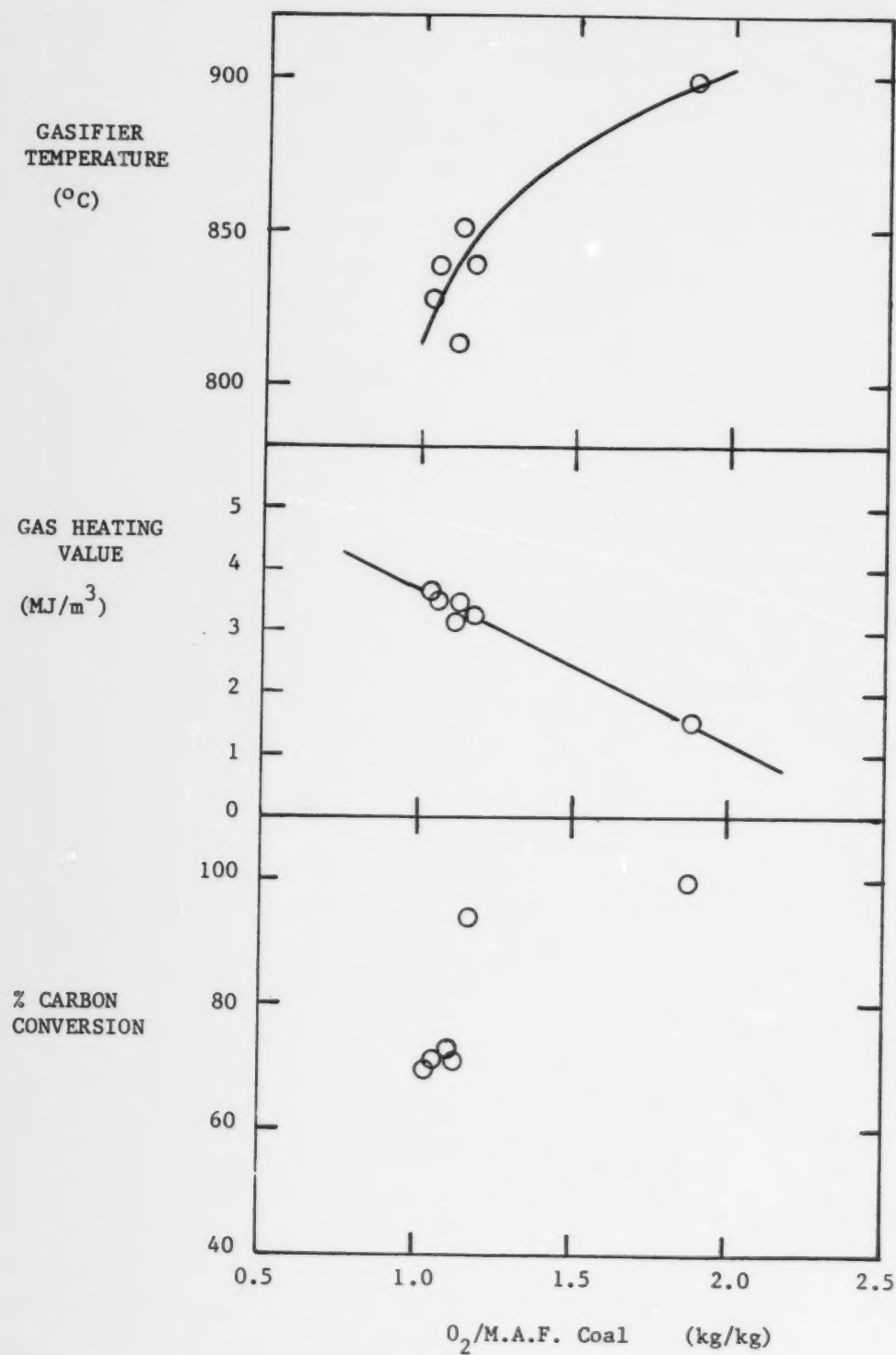


FIGURE 15 Gasifier temperature, gas heating value and carbon conversion versus oxygen/coal ratio for Byron Creek coal air gasification experiments.

using Byron Creek coal -- the feed rate had to be decreased from 5 kg M.A.F. coal/h for Highvale and Coal Valley coals to 3.4 kg M.A.F. coal/h.

Examination of Figure 15 reveals the following:

1. Increasing the oxygen/coal ratio from 1.03 to 1.68 results in an increase in temperature from 750°C to 900°C. The use of different steam/coal ratios between 3 and 5.5 kg H₂O/kg M.A.F. coal in the tests contributes to the spread in the data points.
2. As the oxygen/coal ratio increases, the gas heating value decreases. Gas heating values were typically from 1.5 to 3.65 MJ/m³ over the range of conditions tested.
3. Carbon conversion increases from about 70% to about 90% over a narrow oxygen/coal range of 1.03 to 1.3. Further increases in oxygen/coal ratio result in a gradual increase to almost 100% carbon conversion.

It is clear from Figure 15 that results of the oxygen/coal ratio effect on gas heating value and percent carbon conversion could as well as plotted versus gasifier temperature, which would show similar trends. However, since temperature is dictated primarily by the oxygen/coal ratio, the plot of gasifier performance versus oxygen/coal ratio seems preferable.

Figure 16 shows some additional process response factors plotted in the same way as in Figure 15. The gas yield increases with oxygen/coal ratio and reflects the increasing amount of accompanying nitrogen in the air blast in addition to an increased carbon conversion. The concentrations of both hydrogen and carbon monoxide decline with increasing oxygen/coal ratio. This corresponds to an increased consumption of product hydrogen in reaction

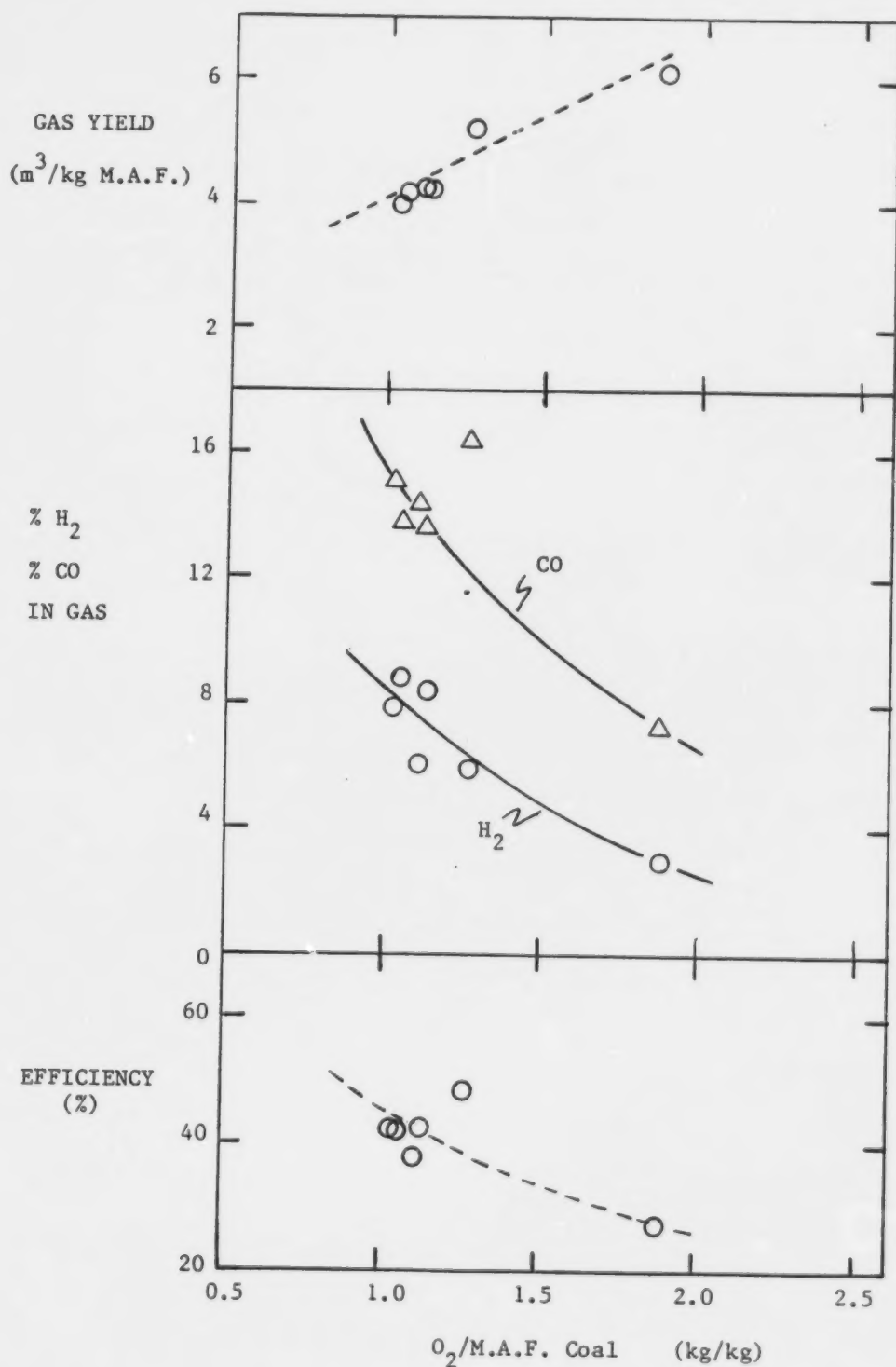


FIGURE 16 Gas yield and composition, and efficiency versus oxygen/coal ratio for Byron Creek coal air gasification experiments

with the incoming oxygen as the oxygen/coal ratio is increased. Higher amounts of oxygen also favor the formation of CO_2 in preference to CO despite the fact that higher temperatures promote the steam-carbon reaction to form H_2 and CO .

There is a decline in gasification efficiency as the oxygen/coal ratio is increased. This occurs because the gas heating value falls proportionately faster than the increase in gas yield. The hydrogen in the product gas is burnt preferentially as the oxygen/coal ratio increases and the system approaches combustion conditions.

Steam decomposition is not presented in graphical form since no measurable amount was determined in three tests while in the other three tests the steam decomposition was very low, about 0.1 kg/kg M.A.F. coal, with no obvious trend relative to oxygen/coal ratio. The low reactivity of the bituminous coal requires that a higher temperature be employed to achieve a given carbon conversion as compared to a more reactive sub-bituminous coal or lignite. The additional energy requirement comes from the combustion of a greater proportion of the carbon in the feed coal. However, as the temperature increases the reaction environment favors hydrogen combustion to produce steam as a by-product. The net amount of steam decomposition thus becomes less and less as the operating conditions become more severe.

Byron Creek Coal: Product Gas Composition

The variation in gas composition is not very pronounced over the range of operating conditions tested, as shown in Table 6. The gas consists of mainly N_2 , CO and CO_2 , with smaller amounts of H_2 and CH_4 . The strongest

gases contained about 8% H_2 , 15% CO and 64% N_2 . Figures 17a to 17c show the calculated equilibrium gas species versus experimental values for CO, CO_2 and H_2 . For each of these three gas species there is a very substantial deviation between the experimental and calculated equilibrium results indicating that the reaction system did not attain chemical equilibrium. The experimental CO composition is higher while the experimental CO_2 and H_2 compositions are much lower than the corresponding equilibrium compositions. However, the deviations are generally consistent such that the changes in the measured compositions are essentially parallel to the calculated changes in the equilibrium compositions. These comparisons indicate that the trends in the experimental compositions are consistent with gas equilibrium constraints for the operating conditions used in the tests, but on no account is equilibrium attained.

The low hydrogen concentration is caused by operation at high temperatures with large amounts of oxidant. The product hydrogen is readily consumed by the incoming oxygen and reduces the quality of the fuel gas as well as reducing the amount of steam decomposition. The tendency for a low hydrogen concentration is supported by the equilibrium model showing that the operating conditions are unfavorable for the formation of large amounts of hydrogen.

Byron Creek Coal: Gasification Process Considerations

Before the conversion of the pilot plant to bottom feeding of coal, a number of attempts were made to feed coal above the reactor bed, as had been done for the gasification of Highvale and Coal Valley coals. Operational difficulties were encountered related to the nature of the coal. Byron

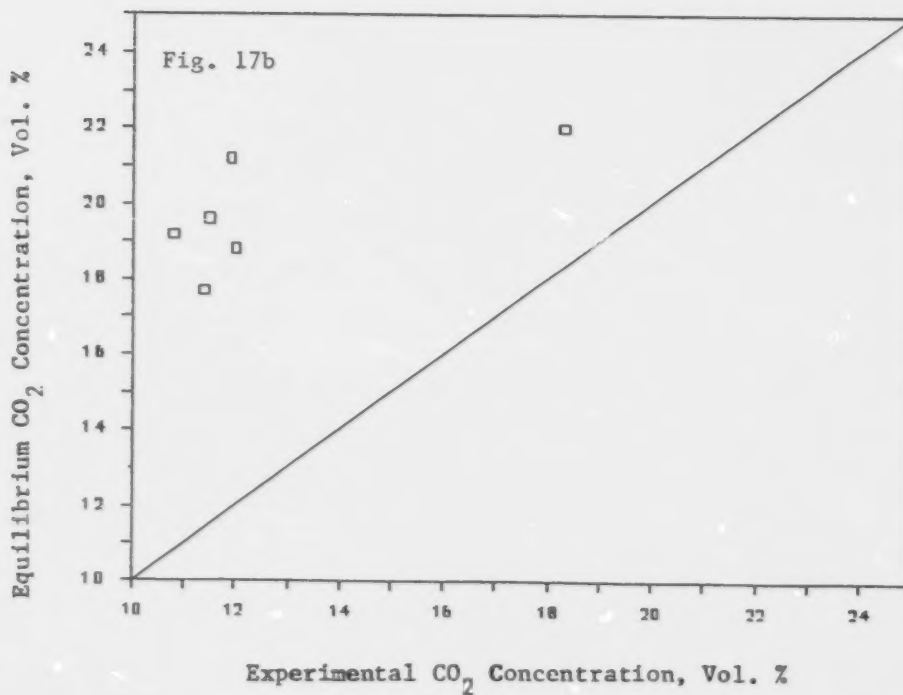
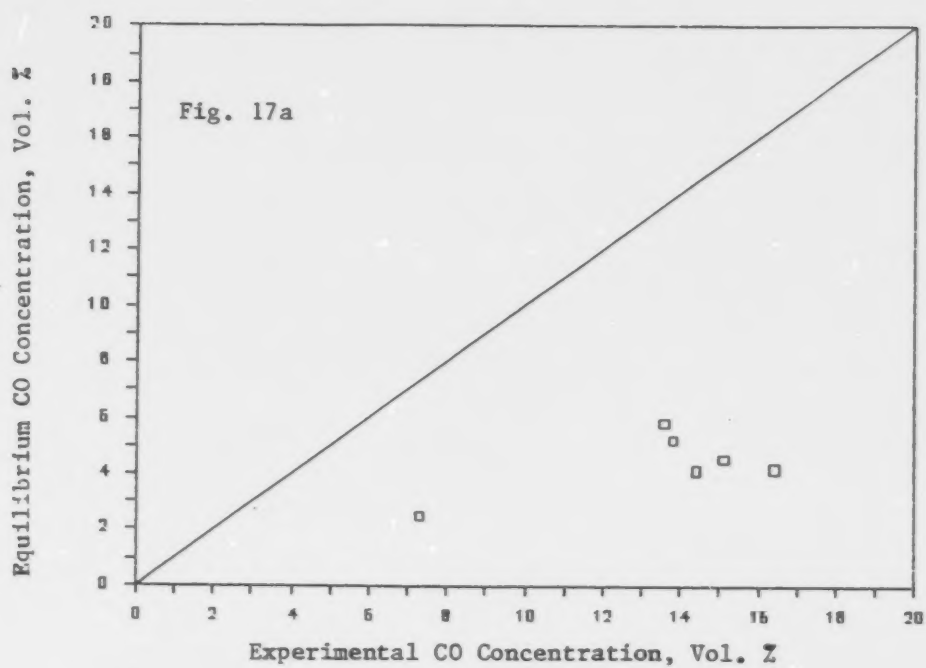


Figure 17: Comparison of Calculated and Measured Dry Gas Compositions for Byron Creek Coal

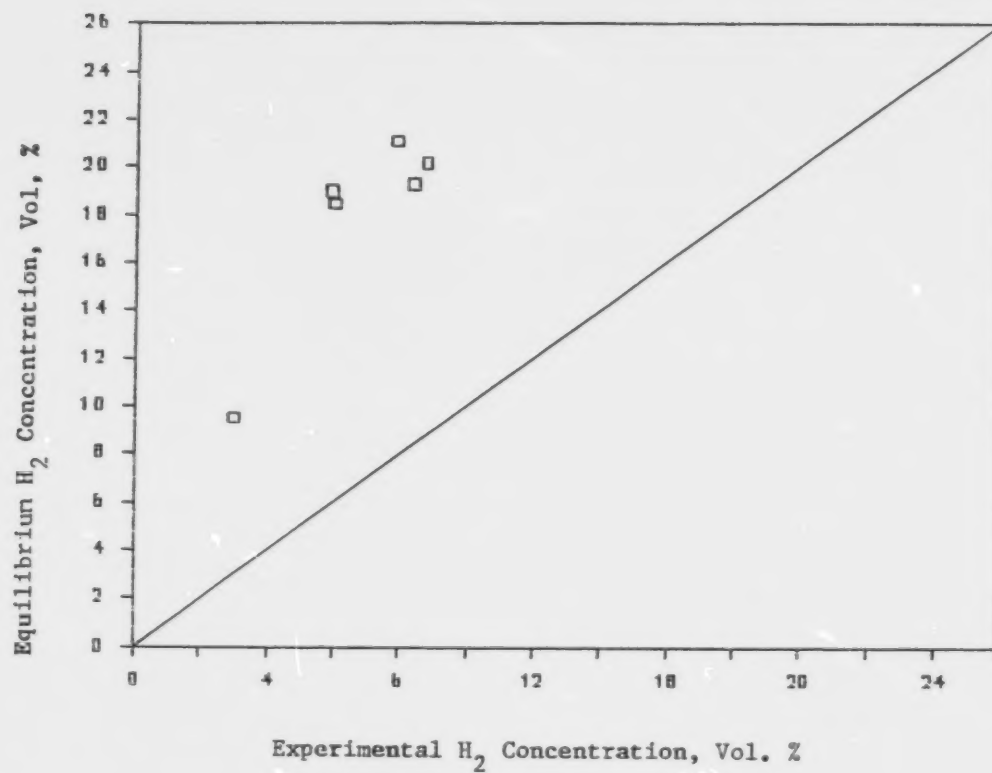


Fig. 17c

Figure 17: Comparison of Calculated and Measured Dry Gas Compositions for Byron Creek Coal

Creek coal swells as it is devolatilized and the residual char is low in density and tends to segregate at the top of the bed. The light char particles form a barrier and the fresh coal dropping from above is unable to mix with the circulating bed. At conditions where the rate of reaction is much lower relative to the coal feed rate there would be an increase in bed inventory and the swollen char would fill the reactor, cutting off the flow of incoming coal. In some tests, depending on the operating conditions, the char particles stuck together to form agglomerates which would then bridge the reactor in a solid mass. This plug would cause a sharp increase in pressure drop across the reactor and reduce the flow of feed materials. The test would have to be terminated and afterwards the reactor bottom flange would have to be removed and the plug chipped out.

The coal feeding difficulties were essentially overcome with bottom feeding of the coal. The injection of coal into the hot central zone causes rapid heating of the particles and the transition through the plastic state is of short duration. The use of inert sand as bed material also serves to promote circulation and reduces the tendency for the particles to stick together. In the successful test runs the residual bed material had no agglomerates and flowed out of the reactor easily.

The reactivity of the coal is lower than that of a sub-bituminous coal or lignite and this, together with the swelling nature of the coal, reduced the range of operating parameters that could be tested. In order to obtain adequate circulation of the particles in the bed the velocity of the rising reactant gases must be maintained above a certain minimum value. In this pilot plant the minimum superficial velocity for good bed circulation was about 0.5 m/sec. Because of the elevated pressures employed, the added

steam is a major fluidizing agent maintaining bed circulation. Although a lower range of oxygen/coal ratios is preferred to obtain improved product gas quality, this would cause a reduction in superficial velocity. Thus the steam rate had to be kept at a sufficient rate to obtain good bed circulation. At the same time steam acts as a quenching agent and a proportionally greater amount of air or oxygen is required to sustain the bed temperature with the high steam rates. These interacting effects place limits on the operating parameters. As a partial solution, the operating pressure was reduced to about 5 atm such that adequate superficial velocity could be maintained at lower steam rates.

Reducing the steam flow has led to bed collapse in some attempts. Increasing the flow rate of oxidant is only a limited solution because of the possibility of going from the desired reducing gasification conditions to an oxidizing atmosphere with excess oxygen appearing in the product gas. This tendency also occurred when the steam and oxidant rates were increased together since a greater amount of oxygen is required for heating both the steam and the nitrogen in the air blast.

The lower reactivity of the coal meant that coal throughput rates had to be reduced to prevent excessive bed buildup. Although higher coal rates can be tolerated in this size of bench scale unit they would require corresponding increases in the air rate beyond the capability of the present system. As a result, the ratios of steam/coal and oxidant/coal do not extend over a wide range. These operational constraints are specific to this pilot plant and type of coal.

Byron Creek Coal: Summary

Six successful tests were reported for Byron Creek coal. Operation was at 5 atm pressure. Coal feed rates averaged 3.4 kg M.A.F. coal/h which represents about a 30% reduction in throughput from the more reactive Highvale coal. Gases produced had H_2/CO mol ratios of about 0.5. Gas heating values reached 3.7 MJ/m^3 which is about the minimum value that is readily burnable, and is slightly below the 3.95 MJ/m^3 of the KRW tests on Highvale coal. The magnitude of the gas heating value achieved reflects the fact that operation was possible only at significantly higher O_2/coal ratios than with the non-caking coals. The smooth inverse correlation of gas heating value with O_2/coal ratio in Figure 15 indicates that reduction of the O_2/coal ratio from 1.03 to 0.8 will permit gas heating value of 4 MJ/m^3 to be achieved. Temperatures averaged about 850°C which is rather low for gasifying bituminous coal. Better performance can be anticipated with higher temperatures and on a larger scale.

Although the coal has a free swelling index of 4.5, modifications to the operating procedures for non-caking coals by switching to bottom feeding permitted satisfactory operation with Byron Creek coal. Residual bed material had no agglomerates and was free flowing.

Prince Hub Coal: Introduction

The composition of the Prince Hub Coal is given in Table 2. Compared to the Byron Creek coal, it is lower in fixed carbon (61.4 vs. 70.8% M.A.F. basis) and higher in volatile matter (38.6 vs. 29.3% M.A.F. basis). The free swelling index of 5.5 is higher than that of Byron Creek coal (FSI = 4.5). The oxygen content (12.8% on an M.A.F. basis) is very high. From the relative amounts of carbon and volatiles it might be expected that Prince coal would be easier to gasify than Byron Creek coal, requiring less severe conditions to achieve comparable gasification results. Results of the gasification tests are summarized in Table 7. The gasifier was de-rated substantially with Prince coal. Feed rates were about one half those of Coal Valley, a non-caking bituminous coal.

Prince Hub Coal: Effect of Oxygen/Coal Ratio

Tests were carried out with air and steam blasts, and in three cases additional oxygen was used. As with the Byron Creek coal, the results are presented primarily as a function of oxygen/coal ratio for consistency and shown in Figures 18 and 19. The temperature varied within a narrow range of 830 to 890°C as a result of constraints on the material flow rates so as to maintain adequate process operability. For a given oxygen/coal ratio the temperature achieved with Prince coal was somewhat lower than with Byron Creek coal and this partly resulted from the use of higher steam rates. The striking feature of the Prince Hub tests is the low magnitude of the gas heating value. The best gas produced contained only 7.6% H₂, and 9.3% CO, and had a heating value of 2.7 MJ/m³. This was a reflection of the high O₂/coal ratios used, which exceeded 1.32 kg/kg compared to 0.5 - 0.8 for

SUMMARY OF RESULTS

PRINCE

Run No		134	138	139	140	162	164
OPERATING CONDITIONS							
Oxidant		Air+O2	Air	Air	Air	Air+O2	Air
Pressure	Atm.	4.16	5.49	6.03	4.81	5.34	5.32
Temperature	C	881	830	846	863	887	889
Coal Rate	kg MAF/hr	1.57	2.56	2.49	3.36	2.20	2.29
Steam Rate	kg/hr	10.5	18.9	18.4	16.7	14.7	12.1
Air Rate	kg/hr	11.4	18.3	24.0	18.9	13.4	14.9
O2 Rate	kg/hr	3.35	0	0	0	3.82	0
Added N2	kg/hr	1.45	0.83	1.06	1.14	0.46	0.56
Sup. Vel.	m/sec	0.54	0.69	0.64	0.76	0.60	0.52
H2O/MAF	kg/kg	7.77	7.44	7.43	4.97	6.75	5.34
Air/MAF	kg/kg	8.39	7.14	9.63	5.62	6.11	6.52
O2/MAF	kg/kg	2.47	1.68	2.26	1.32	1.74	1.53
N2/MAF	kg/kg	7.49	5.79	7.80	4.64	4.88	5.24
RESULTS							
C Conv.	Wt. %	89.8	75.7	92.0	81.8	88.3	86.6
Efficiency	%	8.1	22.1	9.9	34.3	15.5	24.8
H2O Decomp.	kg/kg MAF	0	0	0	0	0	0
H2O Decomp.	Wt. %	0	0	0	0	0	0
DRY GAS ANALYSIS							
H2	Vol. %	0.7	3.7	0.3	5.5	0.7	2.3
N2	Vol. %	79.3	76.5	81.5	72.1	75.7	75.3
CH4	Vol. %	0.2	0.6	0.3	1.1	0.7	0.9
CO	Vol. %	1.9	5.3	2.5	8.6	4.7	6.8
CO2	Vol. %	17.8	13.9	15.5	12.7	18.2	14.7
C2H6	Vol. %	0	0	0	0	0	0
HHV	kcal/m3	103	330	112	536	235	366
HHV	MJ/m3	0.43	1.38	0.47	2.24	0.99	1.53
H2/CO	mol/mol	0.38	0.70	0.12	0.66	0.16	0.34
Gas Yield	m3/kg MAF	6.47	5.50	7.25	5.25	5.38	5.56
WET GAS ANALYSIS							
H2O	Vol. %	60.9	63.1	57.2	54.1	61.9	55.3
EQUILIBRIUM MODEL RESULTS (DRY GAS)							
H2	Vol. %	3.1	9.5	3.3	14.1	6.5	9.8
N2	Vol. %	77.4	72.0	79.0	65.5	71.3	69.5
CH4	Vol. %	0	0	0	0	0	0
CO	Vol. %	0.5	1.1	0.5	2.9	1.2	2.1
CO2	Vol. %	19.0	17.5	17.2	17.5	21.0	18.6
HHV	MJ/m3	0.45	1.35	0.48	2.16	0.98	1.52
H2/CO	mol/mol	6.43	8.52	6.71	4.94	5.67	4.64

SUMMARY OF RESULTS

PRINCE

Run No 169

OPERATING CONDITIONS

Oxidant		Air+O2
Pressure	Atm.	3.99
Temperature	C	854
Coal Rate	kg MAF/hr	2.41
Steam Rate	kg/hr	11.5
Air Rate	kg/hr	12.3
O2 Rate	kg/hr	3.45
Added N2	kg/hr	0.39
Sup. Vel.	m/sec	0.65

H2O/MAF	kg/kg	4.83
Air/MAF	kg/kg	5.11
O2/MAF	kg/kg	1.43
N2/MAF	kg/kg	4.07

RESULTS

C Conv.	Wt. %	89.1
Efficiency	%	38.4
H2O Decomp.	kg/kg MAF	0.03
H2O Decomp.	Wt. %	0.70

DRY GAS ANALYSIS

H2	Vol. %	7.6
N2	Vol. %	66.0
CH4	Vol. %	1.4
CO	Vol. %	9.3
CO2	Vol. %	15.7
C2H6	Vol. %	0
HHV	kcal/m3	648
HHV	MJ/m3	2.71
H2/CO	mol/mol	0.82
Gas Yield	m3/kg MAF	4.86

WET GAS ANALYSIS

H2O	Vol. %	55.1
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EQUILIBRIUM MODEL RESULTS (DRY GAS)

H2	Vol. %	16.7
N2	Vol. %	59.5
CH4	Vol. %	0
CO	Vol. %	3.7
CO2	Vol. %	20.1
HHV	MJ/m3	2.60
H2/CO	mol/mol	4.55

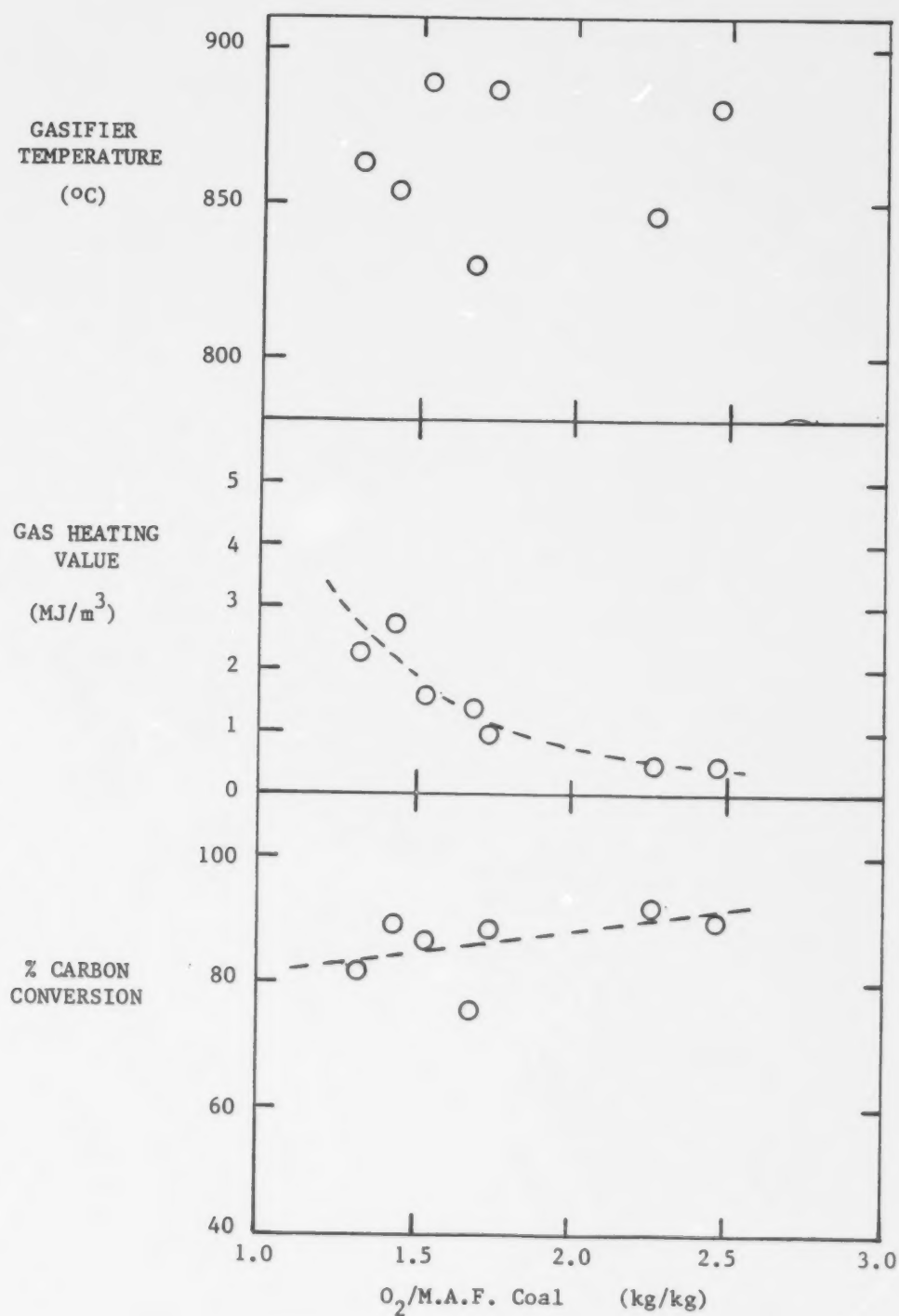


FIGURE 18 Gasifier temperature, gas heating value and carbon conversion versus oxygen/coal ratio for Prince Hub coal air gasification experiments

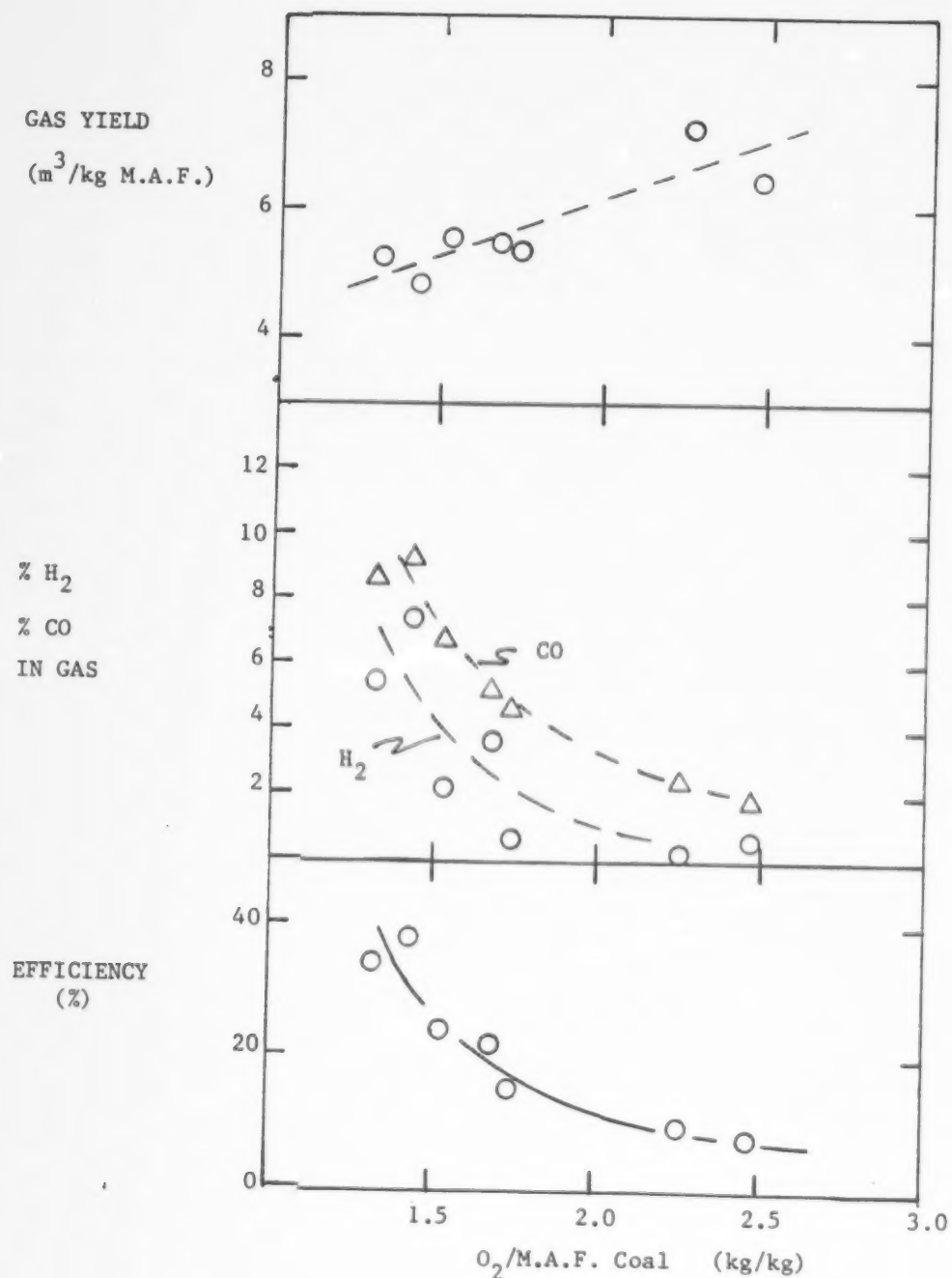


FIGURE 19 Gas yield and composition, and efficiency versus oxygen/coal ratio for Prince Hub coal air gasification experiments

the non-caking Coal Valley coal. The gas heating value declined with increasing oxygen/coal ratio, as was observed with all other coals. The projected higher carbon conversion compared to Byron Creek coal based on proximate coal analysis was realized at low oxygen/coal ratios. At higher oxygen/coal ratios at which the reaction system approached partial combustion conditions there was a lower conversion with Prince coal. However, this may be due to the specific operating conditions (higher steam rate and accompanying lower bed temperature) rather than a definite effect of increased oxygen/coal ratio. Consequently, the most that could be said with the data available is that the carbon conversions for the two coals are of comparable order.

Figure 19 shows trends similar to those observed with Byron Creek coal. There is an increase in gas yield with increasing oxygen/coal ratio caused by the higher amounts of nitrogen in the increased air blast. The concentrations of H_2 and CO decline at higher oxygen/coal ratios and are much lower than those from Byron Creek coal. The efficiency also declines with increasing oxygen/coal ratio and the values are lower compared to Byron Creek coal.

The amount of unreacted water in the tests indicated that there was minimal steam decomposition, i.e. even less than that obtained with Byron Creek coal. The oxygen content of the feed coal is very high (12.8% on an M.A.F. basis) and serves overall as a reactant with product hydrogen to form by-product steam, thereby reducing the net amount of input steam decomposed.

Prince Hub Coal: Product Gas Composition

The composition of the product gas was significantly dependent on the oxygen/coal ratio. At a ratio above about 1.5 the reactor conditions approached sub-stoichiometric combustion and the concentrations of H_2 and CO fell to below 1% and 2%, respectively. A much improved fuel gas composition was obtained at oxygen/coal ratios of 1.3 to 1.5, where there was about 2% H_2 and 5% CO. The concentrations of both H_2 and CO were lower than obtained with Byron Creek coal. In addition to the high oxygen content in Prince coal, there is also significant amount of sulfur (3.6% on an M.A.F. basis) and both of these elements consume hydrogen during gasification. The declining trends in H_2 and CO concentration suggest that the preferred range of operation is at oxygen/coal ratios of less than 1.3, but this was difficult to obtain in this pilot plant because of constraints in material flow rates and heat input capacity. At low oxygen/coal ratios the bed temperature would be too low to obtain adequate carbon conversion which would lead to char sticking problems and interruption of material flows.

The trends in concentrations of the gas components are also generated from the equilibrium model (Figure 20) indicating that the changes in composition follow the constraints of chemical equilibrium. As has often been found for relatively un-reactive coals, the gases do not come to water gas shift equilibrium in the contact time available.

Prince Hub Coal: Gasification Process Considerations

Because of the higher free swelling index, Prince coal was found to be more difficult to process than Byron Creek coal. Prince coal puffed up more readily with a greater tendency to segregate at the top of the reactor.

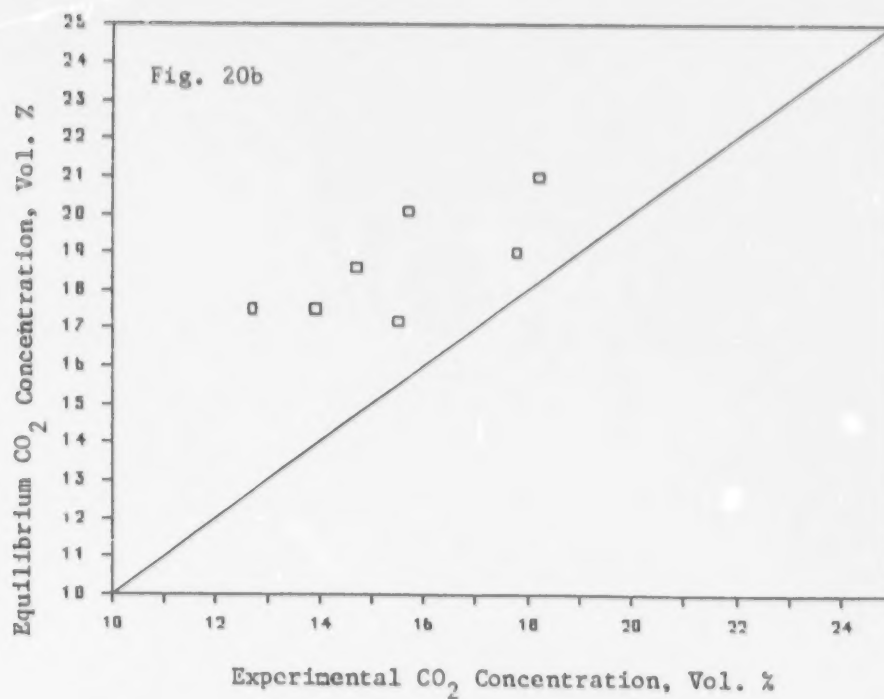
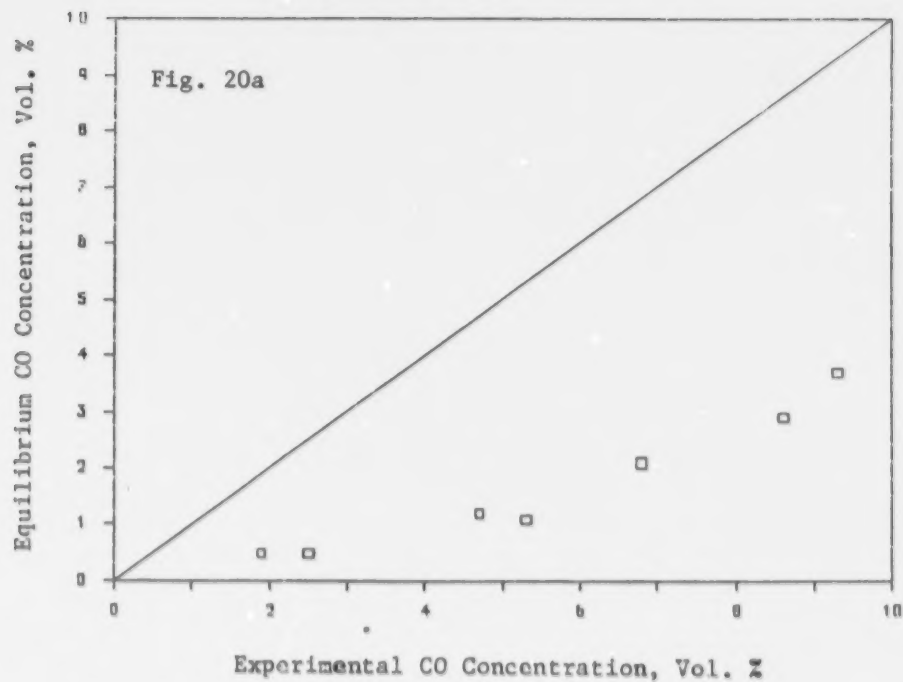
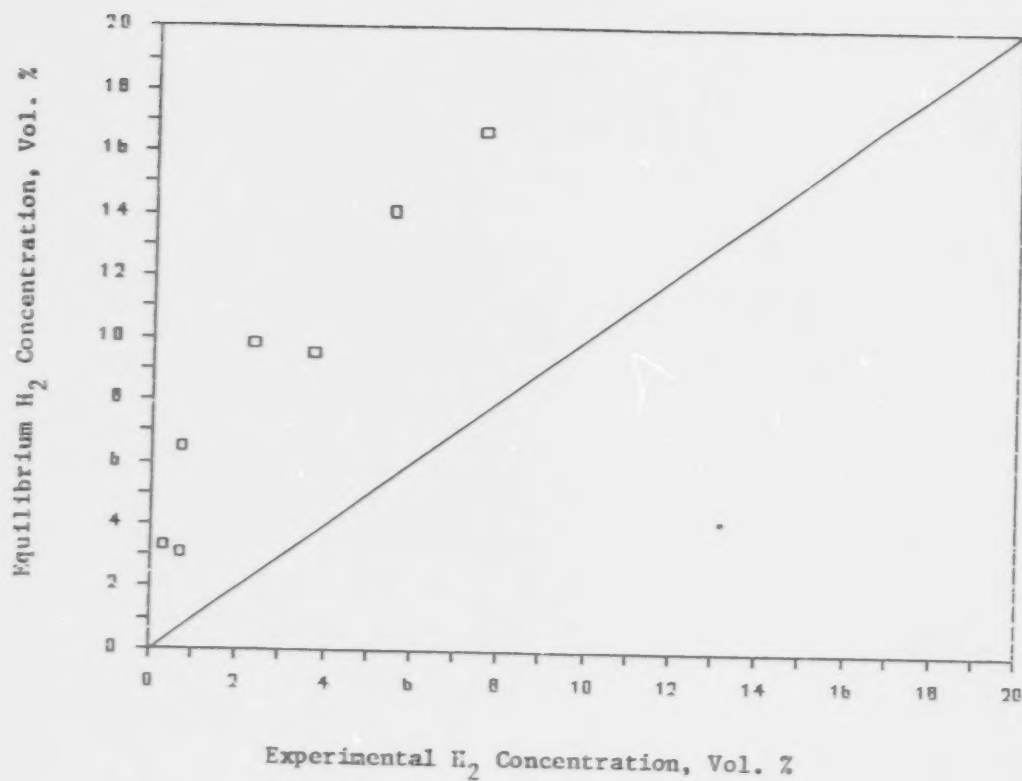


Figure 20: Comparison of Calculated and Measured Dry Gas Composition for Prince Hub Coal



Experimental H_2 Concentration, Vol. %
Fig. 20c

Figure 20: Comparison of Calculated and Measured Dry Gas Compositions for Prince Hub Coal

This further limited the range of operating conditions that could be successfully employed, so that the results obtained are not for the same ranges of operating parameters as with Byron Creek coal. The coal throughput was lower and the oxygen/coal ratio generally higher than used for Byron Creek coal.

Although the swelling nature of the coal was the major source of difficulty, the successful tests carried out at the right balance of operating parameters were relatively problem free. As with Byron Creek coal the residual bed material contained no agglomerates and flowed out of the reactor with ease. The operating difficulties arose when attempts were made to extend the ranges of conditions beyond the narrow operating window. Unfortunately, the preferred ranges for gasification were not completely covered which reflects a combination of the physical limitations of the reactor system and the swelling nature of the coal.

The high oxygen content of Prince coal means that the actual oxygen/coal ratios in the reactor are higher than the numbers recorded from the oxygen content of the gas feed alone in the results. This is aggravated by the use of relatively higher blast oxygen rates, which are needed to maintain stable process operations. Thus the poor gas quality and especially the low hydrogen concentrations are the result of the combination of coal quality and pilot plant limitations.

Prince Hub Coal: Summary

Seven test runs were reported for Prince Hub coal. Coal feed rates averaged 2.4 kg M.A.F. coal/h, which represents about 50% of the throughput possible with the more reactive Highvale coal. Gases produced had H_2/CO mol

ratios of about 0.5. Gas heating values reached 2.7 MJ/m^3 at O_2/coal ratio of 1.43 which is well below the 3.95 MJ/m^3 of the KRW test on Highvale coal at O_2/coal ratio of 1.09. An inverse correlation of gas heating value with oxygen/coal ratio indicated that reduction of the O_2/coal ratio to the latter value is essential to obtain gas heating values in the range applicable for IGCC operation. Temperatures in the gasifier averaged about 865°C , which is higher than those achieved with Byron Creek coal, and was obtained by the higher O_2/coal ratio. Reduction in steam flow would permit this temperature to rise, but hydrodynamics would be severely affected.

The free swelling index of 5.5 for Prince Hub coal resulted in difficulties in processing which limited the range of successful operating conditions in the 0.1 m dia. gasifier. Within this range which permitted smooth fluid bed operation, the residual bed material contained no agglomerates and was free flowing.

Pittsburgh Seam Coal: Introduction

Pittsburgh Seam coal is a high volatile highly caking coal which has been used by many investigators as a reference coal in gasification studies or as a material to assess gasifier capability. Not all gasifiers are able to process Pittsburgh coal. In particular, fixed bed gasifiers are known for their inability to handle highly caking coals unless special measures are taken to break up the agglomerates. Entrained bed gasifiers are more suitable for such coals since they generally operate at more severe operating conditions which can overcome the caking tendency. With special attention to dilution or pretreatment to reduce caking, fluidized gasifiers may be used however.

Several attempts were made to gasify Pittsburgh Seam coal but only four were successful. Because of the limited number of data points the results are not presented graphically and instead comparisons are made with the other bituminous coals. Of the bituminous coals tested Pittsburgh coal has the highest amount of volatiles and the least amount of fixed carbon. The free swelling index is the highest. Based on the tests with Byron Creek and Prince coals, Pittsburgh coal should be expected to be more difficult to process.

Pittsburgh Seam Coal: Effect of Oxygen/Coal Ratio

As shown in Table 8, gasification data were obtained at oxygen/coal ratios of 0.74 to 1.63. For two tests at intermediate oxygen/coal ratios a finer coal size of 1 mm was used. As expected, there is an increase in bed temperature with increasing oxygen/coal ratio. The results indicate that bed temperature is more sensitive to oxygen/coal ratio with Pittsburgh coal

SUMMARY OF RESULTS

PITTSBURGH SEAM

Run No		170	177	184	187
OPERATING CONDITIONS					
Oxidant		Air	Air+O2	Air	Air
Pressure	Atm.	3.76	4.13	4.54	4.95
Temperature	C	814	907	865	868
Coal Rate	kg MAF/hr	2.81	2.53	2.46	2.36
Steam Rate	kg/hr	9.49	9.95	9.56	12.3
Air Rate	kg/hr	8.87	13.8	12.0	12.9
Total O2	kg/hr	2.08	4.12	2.83	3.04
Added N2	kg/hr	0.40	0.38	0	0.33
Sup. Vel.	m/sec	0.54	0.58	0.52	0.56
H2O/MAF	kg/kg	3.40	3.96	3.90	5.25
Air/MAF	kg/kg	3.16	5.47	4.89	5.49
O2/MAF	kg/kg	0.74	1.63	1.15	1.29
N2/MAF	kg/kg	2.56	4.34	3.75	4.34
RESULTS					
C Conv.	Wt. %	57.1	74.9	91.8	82.4
Efficiency	%	34.5	16.3	49.4	30.8
H2O Decomp.	kg/kg MAF	0.10	0	0.08	0
H2O Decomp.	Wt. %	2.87	0	2.00	0
DRY GAS ANALYSIS					
H2	Vol. %	9.7	0.9	10.5	2.1
N2	Vol. %	63.7	74.0	59.0	70.7
CH4	Vol. %	1.7	0.9	1.2	0.9
CO	Vol. %	13.6	6.1	15.0	13.1
CO2	Vol. %	11.3	18.1	14.3	13.2
C2H6	Vol. %	0	0	0	0
HHV	kcal/m3	869	295	885	548
HHV	MJ/m3	3.64	1.23	3.71	2.30
H2/CO	mol/mol	0.71	0.14	0.70	0.16
Gas Yield	m3/kg MAF	3.25	4.52	4.57	4.59
WET GAS ANALYSIS					
H2O	Vol. %	55.8	53.6	51.0	59.7
EQUILIBRIUM MODEL RESULTS (DRY GAS)					
H2	Vol. %	21.9	7.7	19.8	13.8
N2	Vol. %	55.0	68.9	53.0	62.2
CH4	Vol. %	0	0	0	0
CO	Vol. %	4.2	2.1	5.5	2.9
CO2	Vol. %	18.9	21.3	21.7	21.1
HHV	MJ/m3	3.33	1.24	3.26	2.12
H2/CO	mol/mol	5.29	3.63	3.57	4.84

than with the other bituminous coals. A relatively higher temperature was attained at the same oxygen/coal ratio than with other bituminous coals.

At the oxygen/coal ratio of 1.15 the heating value of the product gas, at 3.7 MJ/m³ is comparable to that obtained with Byron Creek coals.

Reducing oxygen/coal ratio to 0.74 surprisingly left the gas heating value unchanged although it was produced at a relatively lower temperature of 814°C. This is a reflection of the higher volatile content of Pittsburgh coal as the carbon conversion is only 57% compared to 72% with Byron Creek coal at a similar temperature. These volatiles are more readily consumed as the oxygen/coal ratio is increased and this results in a poorer quality gas with the carbon conversion still remaining lower than the other coals.

Gas yield increases with increasing oxygen/coal ratio as a result of the increased air blast as well as increased carbon conversion.

The hydrogen concentration of 10.5% at the oxygen/coal ratio of 1.15 was the highest obtained for any of the caking bituminous coals. The CO concentration of 15% was comparable to that produced from Byron Creek coal at the same temperature.

Cold gas efficiency declines as the oxygen/coal ratio increases conforming to the reduction in the quantities of combustible components.

Pittsburgh Seam Coal: Product Gas Composition

The gas produced at an oxygen/coal ratio of 1.15 was the best in terms of fuel gas quality because of the high amounts of H₂ and CO. This results in part from devolatilization of the high volatile coal and this advantage is lost when the oxygen/coal ratio is increased to 1.63 since the volatiles become the reactants of preference as attempts are made to raise the

operating temperature through increased combustion. There are significant differences in gas composition between experiments and predictions of the chemical equilibrium model. CO values are about a factor of three higher, and H₂ values about a factor of two lower than predicted.

Pittsburgh Seam Coal: Gasification Process Considerations

The swelling nature of Pittsburgh coal (F.S.I. = 7) added to the difficulties in obtaining stable gasification operations. In the first few tests with this coal reactor plugging was observed, indicated by a high pressure drop across the reactor. Unlike with Prince coal where the char bridged the upper section of the reactor, effectively terminating the flow of materials, the plug that formed with Pittsburgh coal would break away within a few minutes of forming and the material flows would resume. This phenomenon would occur repeatedly and eventually lead to loss of operability from the cooling down of the reactor caused by the interruptions. The problem was traced to the deposition of char at the tip of the coal guide tube (Figure 2b) where the coal entered the reactor. Combustion occurring in this zone made the tip hot enough to cause the incoming coal to become plastic and stick to the wall of the coal feeding tube. This would break away or burn away thus clearing the plug. This plugging of the coal guide tube was solved by cutting an inch off the tip of the tube so that the coal would become surrounded by steam at that point as well as by reducing the amount of heating on the coal conveying line to reduce the extent of coal preheating before the coal reaches the hot combustion zone.

The swelling nature of this coal also created difficulties after the coal entered the reactor. There was a tendency to form char agglomerates up

to about 30 mm in size which destabilized the circulation pattern of the bed. This would cause "bumping" in the reactant flows with the indicator floats of the air and oxygen rotameters oscillating to varying degrees in an irregular fashion. The agglomerates were less prone to form a continuous mass bridging the reactor as was observed with Prince coal. However, the bed destabilization would be severe enough in some tests to cause bed segregation or bed settling and this would result in a local temperature runaway. The temperature would be sufficiently high to cause ash fusion or fusion of the ash with the sand particles. This would generally result in the formation of porous clumps of sand and ash loosely adhering together, or in some cases tightly bound glassy clumps. Stable operations could not be maintained when these clumps formed.

In addition to the difficulties caused by the swelling nature of the coal, Pittsburgh coal was not particularly reactive thereby requiring a high temperature to get acceptably high rates of carbon conversion. Achieving higher temperatures was more difficult to accomplish in practice than with the other bituminous coals. Increasing the oxygen/coal ratio caused a greater combustion of the volatiles and this manifested itself in a higher temperature response with changes in the oxygen/coal ratio and a significantly poorer fuel gas quality. The system temperature was more difficult to control and the useable ranges of operating parameters reduced. The corollary to the ease of combustion of the volatiles contained in this less reactive coal is less reactive residual char. It was not possible to sustain combustion when the bed temperature fell below 700°C with Pittsburgh coal whereas this could be accomplished with the other two coking bituminous coals. Thus startup operations at too low a temperature could encounter

inability to initiate combustion while too high a temperature could cause a temperature runaway.

The successful tests with Pittsburgh coal were the result of a gradual transition from the reactive Highvale coal (used to bring up the bed temperature) at the right balance of conditions that allowed the appropriate mix of high volatile fresh feed coal and less reactive bed char. The transition was accomplished within the narrow operating window and produced meaningful gasification results. The use of the smaller coal feed size in Runs 184 and 187 permitted a smoother operation at the intermediate O_2 /coal ratios. Unfortunately, attempts to conduct tests to investigate a wider range of conditions were not successful.

Comparison of the Gasification Results with Different Coals

In this work gasification tests have been made with coals of differing ranks and compositions. With a gasifier of a given geometry, and the necessity to maintain the bed of particles in a spouting/fluidized mode which dictates a minimum velocity, the gasifier throughput becomes a measure of reactivity. Furthermore as the coal reactivity decreases, the temperature of operation must be increased at a given coal input rate. Table 9 indicates average conditions and some specific results for the five coals tested. It is evident that the average coal feed rate is substantially lower, and the required temperature is higher for gasifying the higher rank coals. Generally the gas quality also decreases as the coal rank increases, other things being constant. At an O_2 /coal ratio of 1.0, the gas heating value is highest for Highvale, and roughly the same for Coal Valley, Byron Creek, Prince Hub and Pittsburgh Seam coal.

TABLE 9 Comparison of Air Gasification with Different Coals

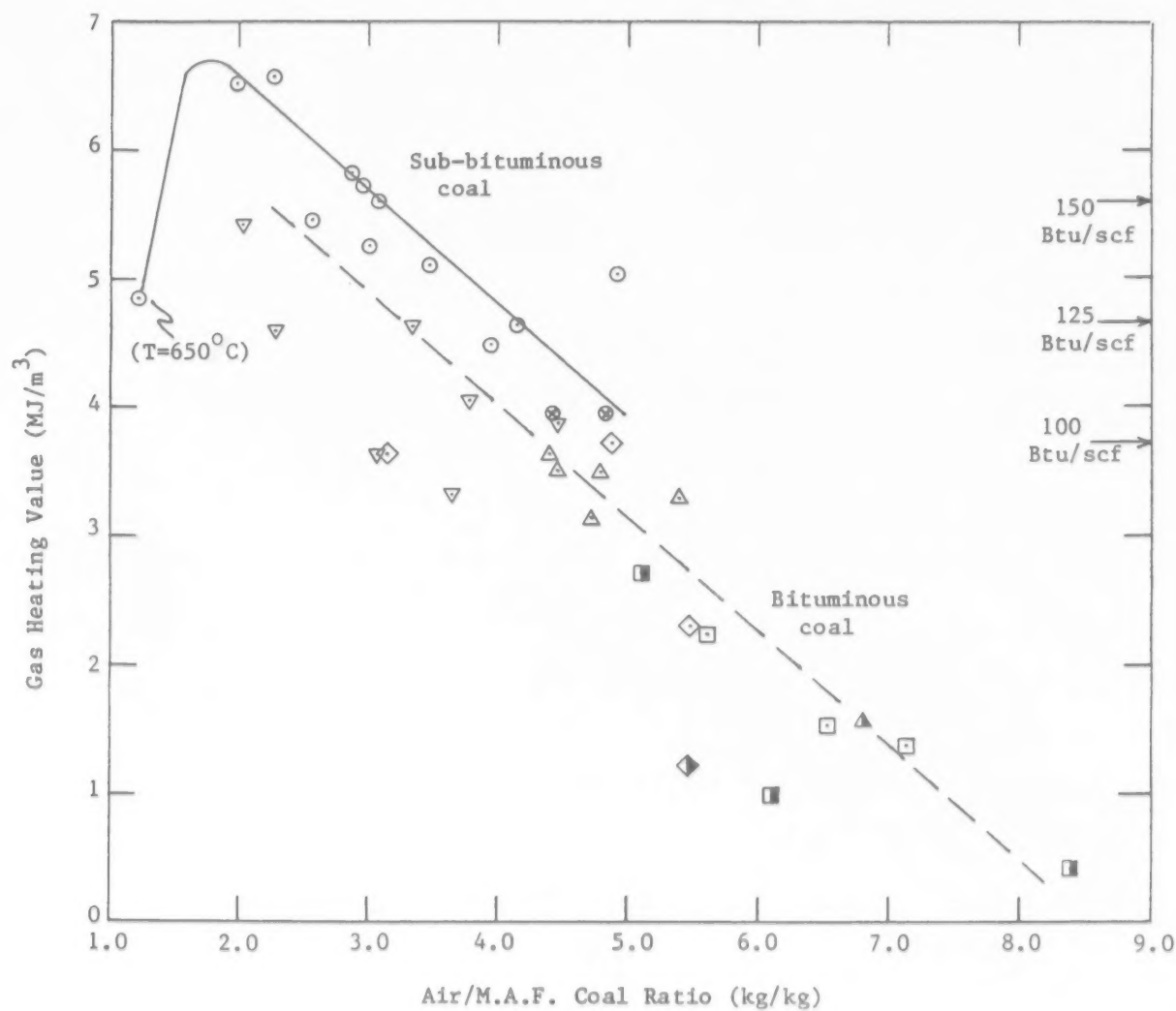
Coal	Highvale	Coal Valley	Byron Creek	Prince Hub	Pittsburgh Seam
Rank	Sub-Bit.	H.V. Bit.	M.V. Bit.	H.V. Bit.	H.V. Bit.
Average M.A.F. coal feedrate (kg/h)	4.9	5.1	3.4	2.4	2.7
Average bed temperature °C	731	813	845	865	860
Gas heating value at air/coal = 4 (MJ/m ³)	4.6	4	4	3.5*	2.9
Maximum gas heating value (MJ/m ³)	6.5	5.4	3.7	2.7	3.6
Minimum air/coal ratio kg/kg	2.1	2.0	4.4	5.2	3.1

*Extrapolated

Figures 21 and 22 show the air-steam gasification data for all coals plotted as gas heating value versus air/coal and oxygen/coal ratio respectively. The gasifier could be operated at low air (or oxygen) to coal ratios for the more reactive coals - Highvale and Coal Valley. As has been stressed throughout this report, the Highvale coal yields the strongest gas. It is interesting to note that all the bituminous coals - the Coal Valley, Byron Creek and Prince Hub and Pittsburgh Seam coal data all lie along a single line, within some scatter. This illustrates that at a given air (or oxygen) to coal ratio, all four of these coals will yield gas of similar heating value. It is only the constraints of the present reactor system which fixed the minimum O_2 /coal ratio and has resulted in average heating values being higher for Coal Valley, than for Byron Creek which itself was higher than Prince Hub. The data on Pittsburgh Seam coal is meager, but appears to fit those of the other coals. Further data are needed.

This pilot scale gasifier is a small unit and, due to heat loss problems, for the low feed rates of the caking bituminous coals temperatures were inadequate for high carbon conversion unless the oxygen/coal ratio was raised. In a larger scale unit, or one with the capability of substantial air pre-heating, it would be possible to decrease the oxygen/coal ratio to about 0.8-1.0 without having the temperature decrease correspondingly, and a direct comparison of all five coals in near optimum gasification conditions could be made. A preheater has been designed, and will be incorporated in future tests.

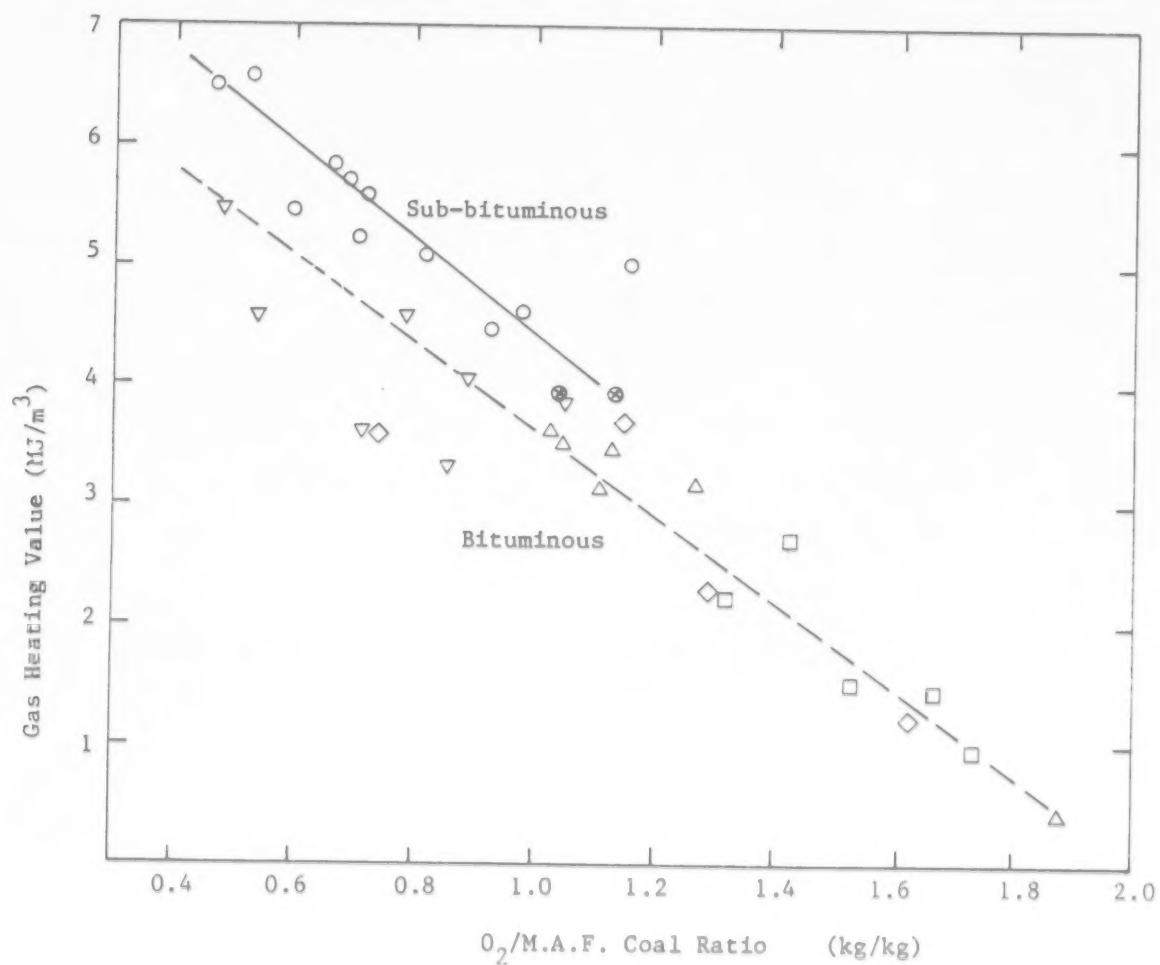
The results of this study discussed above and Figures 21 and 22, also indicate that all coals tested can be accommodated in the spouted/fluidized



Legend

- Highvale
- ⊗ Highvale (KRW tests)
- ▽ Coal Valley
- △ Byron Creek
- Prince Hub
- ◇ Pittsburgh Seam
- Half shaded symbols: Air + O_2

Figure 21: Plot of Gas Heating Value versus Air/Coal Ratio for All Coals



Legend

- Highvale
- ⊗ Highvale (KRW tests)
- ▽ Coal Valley
- △ Byron Creek
- Prince Hub
- ◇ Pittsburgh Seam

Figure 22: Plot of Gas Heating Value Versus Oxygen/Coal Ratio for All Coals

bed gasifier, and it is a matter of arranging the appropriate gasifier temperature and air (or oxygen) coal ratio to generate a gas suitable for combustion, for example in IGCC plant.

The preferred operating conditions for gasification of the bituminous coals would include steam/coal ratios less than 3 and oxygen/coal ratios less than 1.3. The operating temperatures should be above 800°C and preheating of the air would be needed to achieve the high temperatures. The size, flow rate and heating rate of the coal particles have to be controlled to avoid char agglomeration in the case of the caking coals.

During the course of these tests the equipment downstream of the reactor was disassembled for cleaning on several occasions. This problem no doubt was exacerbated by the number of experimental attempts which were unsuccessful in reaching good gasification conditions. There was a significant amount of tar-like material which would condense out from the product gas stream at locations where the gas experienced a temperature drop. The feed water/product gas heat exchanger became severely plugged. Steam cleaning and solvent washing failed to dislodge the obstruction and finally the tube bundle was pulled out. This required considerable effort with the use of 5-ton winches. The tube bundle was encrusted with char and ash, held together by the tarry material. Further downstream of the heat exchanger tarry deposits had to be cleaned periodically from the gas cooler where condensation of the excess water in the product gas occurs. The high volatile content of the bituminous coals was the main source of these tarry deposits.

The results obtained in this study show the differences between gasification behaviour of the coals, the measures that need to be taken to

gasify them in a spouted/fluidized bed reactor, the preferred ranges of operating conditions and the quality of gas produced. They form a good basis for understanding the gasification characteristics of Canadian coals and indicate areas of future opportunity for continued study.

Conclusions

Conclusions are written for each specific coal tested, followed by more general conclusions on the comparison of the coals tested.

Highvale Coal

1. As the air/M.A.F. coal ratio is increased from 1.2 to 4.9 (kg/kg) at pressures of 7-9 atm the gasifier temperature increased from 650 to 800°C, the gas heating value decreased from 6.5 to about 4.5 MJ/m³, and the H₂/CO molar ratio decreased from 5.2 to 1.5. The corresponding carbon conversion increased with air/coal ratio from 40% to virtually 100%, and the gas yield from 2 to 6.2 m³/kg M.A.F. coal. Cold gas efficiency also increased with air/coal ratio, reaching between 75 and 90% at air/coal > 3.
2. With an oxygen/steam blast the gas heating values exceeded 10 MJ/m³, the corresponding gas yields were about 2 m³/kg M.A.F. coal. Carbon conversions were higher in the oxygen/steam blast probably because of the higher gasifier temperatures.
3. Pressure had little effect on gasifier performance factors over the range 5-14.4 atm.
4. When the KRW data were corrected for the higher nitrogen content of the blast, gas heating values were comparable to those observed in the

present tests. Gas yield and H_2/CO molar ratios were also comparable.

Coal Valley Coal

1. Gasifier temperature was relatively insensitive to air/coal ratio and most air/steam tests were carried out at $800 \pm 40^\circ C$. Gas heating value trended downwards with increasing air/coal ratio decreasing from 5.5 MJ/m^3 at air/coal of 2 to about 3.7 MJ/m^3 at air/coal ratio of 3.8 ($O_2/coal = 0.9$). Carbon conversions were lower than for the Highvale coal, being below 80% at air/coal ratios which gave gases of > 3.7 MJ/m^3 . Gas yields were comparable to those achieved in the Highvale tests, but cold gas efficiencies were all below 60%.
2. Oxygen/steam gasification tests resulted in gas heating values of 9.9 MJ/m^3 on a N_2 -free basis. Carbon conversions were higher at about 87% than in air.
3. As with Highvale coal, pressure effects in gasification of Coal Valley coal were not highly significant.
4. Gases from lower rank coals were in only rough agreement with equilibrium predictions. Hydrogen contents were typically 25% lower than predicted, while CO and CO_2 contents were considerably closer.

Byron Creek Coal

1. Air gasification tests at 5 atmospheres pressure showed that gases of heating value 3.7 MJ/m^3 could be produced at $830^\circ C$ with feed rates of 3.4 kg M.A.F. coal/h. Gas heating value correlated inversely with

O_2 /coal ratio. A reduction of O_2 /coal from 1.03 to 0.8 should increase gas heating value to 4 MJ/m³.

2. Gas H_2 /CO mol ratios were about 0.5 which was far below the equilibrium values of about 4. Thus equilibrium is not achieved, primarily due to preferential oxidation of H_2 .
3. Carbon conversion was typically 71%. A higher gasification temperature achieved without an increase in O_2 /coal ratio would increase this value and improve operation generally.
4. The caking nature of Byron Creek coal (F.S.I. = 4.5) necessitated a switch to bottom feeding. In the range of smoother operation of the gasifier bed, residues were free flowing and without agglomerates.

Prince Hub Coal

1. Air gasification tests were carried out at higher than desirable O_2 /coal ratios in order to increase the gasifier temperature. Gas heating value of 2.7 MJ/m³ was achieved at O_2 /coal = 1.43, and a bed temperature of 854°C. Coal was fed at 3.4 kg M.A.F./h.
2. The relation between gas heating value and O_2 /coal ratio which was established, suggested that a heating value of 4 MJ/m³ would be reached at O_2 /coal of about 0.92.
3. Gases were low in H_2 , with H_2 /CO ratios of about 0.7-0.8; while equilibrium calculations suggested a ratio of 4.5 for the conditions employed. Thus gases leaving the gasifier were not in equilibrium.
4. Carbon conversion was between 80 and 90%. However this was achieved due to the high O_2 /coal ratios.

5. The caking tendency of Prince Hub coal (F.S.I. = 5.5) resulted in smooth operation only within a limited range of conditions. Under such conditions the bed operated smoothly, and the residual material from the bed contained no agglomerates.

Pittsburgh Seam Coal

1. Only limited success was achieved in gasifying Pittsburgh Seam coal in air and steam. At O_2 /coal ratios of 0.74 and 1.15 a gas of heating value 3.6-3.7 MJ/m³ was produced at temperatures of 814°C to 865°C. Further tests are required on this highly caking (F.S.I. = 7) coal.

Comparative Results of Five Coals

The gasification test work carried out in this program shows a continuum of behaviour of all the coals tested which is best seen on the plot of gas heating value versus air or oxygen to coal ratio.

1. Highvale, the most reactive coal, produced the strongest gas at the highest feed rate and lowest temperature. At the same air/coal ratio gas heating value was about 0.6 to 0.8 MJ/m³ higher for Highvale than for any other coal.
2. Coal Valley, Byron Creek, Prince Hub and Pittsburgh Seam coals produced the same gas heating value at a given oxygen/coal ratio.
3. Within limits, all coals could be gasified without pre-treatment in the spouted/fluidized bed. Although optimal conditions were not reached for all coals, results showed consistent trends which with limited extrapolation predict the conditions necessary for IGCC gas production.

4. With less reactive (higher rank) coals, gasifier throughput is lowered, and operating temperatures must be raised to produce suitable gases. All coals produced bed residues which were free-flowing and did not contain agglomerates under optimum conditions.

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APPENDIX A

Steady State Material Balances

Material balances are calculated at steady state conditions based on the flow rates of materials entering and leaving the reactor. The results are shown in Tables A.1 to A.5 for Highvale, Coal Valley, Byron Creek, Prince Hub and Pittsburgh Seam coals, respectively. The input rates for coal and reactant gases and the output rate for product gas are measured independently. In some of the tests independent measurements of the unreacted water are available. Where unavailable, the excess water is derived from a hydrogen mass balance, calculated using the difference between input hydrogen and hydrogen in the product gas. In such cases the hydrogen mass balance closure is 100%. The output rate of reacted coal is calculated from the carbon mass balance as the difference between input carbon and carbon in the product gas. The ash associated with the amount of carbon gasified is reported as the ash in reacted coal. Elemental mass balances for nitrogen, hydrogen and oxygen are also calculated for the steady state periods. The carbon elemental balance is not reported since it is used as the basis for calculating unreacted coal and is always 100%.

Overall Mass Balance

Overall mass balances are calculated as the cumulative amounts of materials entering and leaving the reactor for the entire duration of each test. The mass balances, broken down into the elemental compounds, are included in Appendix A and listed by the test run number. The cumulative amounts of all materials are measured independently, with the exception of those cases where an independent measurement of excess water is not available. For these exceptions the excess unreacted water is calculated by difference. The cumulative amount of product gas is calculated from the steady state gas flow rate and the duration of the steady state plus an additional amount needed to reach steady state. The additional amount is calculated as the product of the steady state gas flow rate multiplied by half the time needed to reach steady state. This is equivalent to the assumption of a proportional change of gas rate with time up to the point that steady state is reached. Analysis for sulfur was not made in this series of tests.

Table A.1

STEADY STATE MATERIAL BALANCE

HIGHVALE COAL

Run No.	73	77	90	75.1	75.2	80
Press., atm	4.7	9.8	8.9	5.2	4.8	7.1
Temp., C	736	880	692	789	901	621
INPUT RATE (kg/hr)						
By Material:						
Coal (as rec.)	11.23	12.89	9.90	7.20	5.55	7.66
Oxygen or Air	3.27	5.58	3.58	15.12	15.28	10.57
Added Steam	5.25	12.74	19.99	3.48	3.12	8.34
Added N ₂	1.23	1.32	1.72	1.45	1.49	1.27
	=====	=====	=====	=====	=====	=====
Total Material In	20.98	32.53	35.19	27.25	25.44	27.84
By Element:						
Nitrogen	1.23	1.32	1.72	13.02	13.19	9.37
Hydrogen	1.81	2.10	2.75	0.77	0.64	1.33
Oxygen	11.31	20.78	24.33	8.80	8.03	12.20
OUTPUT RATE (kg/hr)						
By Material:						
Dry Unreacted Coal	4.05	0.28	2.01	0.57	0.00	2.95
Dry Product Gas	10.09	19.83	14.75	23.19	21.99	12.70
Excess Steam	5.87*	11.18*	18.28	2.45*	2.84*	7.97*
Ash in Reacted Coal	0.75	1.49	0.88	0.77	0.67	0.48
	=====	=====	=====	=====	=====	=====
Total Material Out	20.75	32.78	35.92	26.98	25.50	24.10
By Element:						
Nitrogen	1.03	1.45	1.62	13.18	13.45	6.85
Hydrogen	1.81*	2.10*	2.83	0.77*	0.64*	1.33*
Oxygen	11.35	21.04	26.09	8.46	7.83	11.02
BALANCE (Out/In)						
Total Material	0.989	1.008	1.021	0.990	1.002	0.866
Nitrogen	0.989	1.098	0.941	1.012	1.020	0.732
Hydrogen	1.000	1.000	1.028	1.000	1.000	1.000
Oxygen	1.004	1.013	1.073	0.961	0.976	0.904

* By difference

Table A.1

STEADY STATE MATERIAL BALANCE

HIGHVALE COAL

Run No.	83.1	83.2	83.3	83.4	85	86
Press., atm	9.6	8.4	7.7	9.8	9.1	8.9
Temp., C	650	655	682	699	755	780
INPUT RATE (kg/hr)						
By Material:						
Coal (as rec.)	7.35	7.35	7.35	7.35	6.66	4.77
Air	6.24	9.86	13.11	11.61	16.14	16.36
Added Steam	17.61	17.61	12.44	12.44	12.22	14.07
Added N2	1.95	1.97	1.77	1.75	1.85	1.96
	=====	=====	=====	=====	=====	=====
Total Material In	33.15	36.79	34.67	33.15	36.87	37.16
By Element:						
Nitrogen	6.72	9.51	11.80	10.64	14.21	14.49
Hydrogen	2.35	2.35	1.77	1.77	1.71	1.82
Oxygen	19.32	20.17	16.34	15.99	16.65	17.78
OUTPUT RATE (kg/hr)						
By Material:						
Dry Unreacted Coal	3.55	2.79	2.04	1.09	0.33	0.00
Dry Product Gas	11.55	14.67	17.01	18.18	22.33	22.60
Excess Steam	17.29*	16.83*	11.14*	10.46*	10.48*	11.95*
Ash in Reacted Coal	0.36	0.47	0.58	0.72	0.74	0.74
	=====	=====	=====	=====	=====	=====
Total Material Out	32.75	34.76	30.76	30.45	33.88	35.29
By Element:						
Nitrogen	6.38	7.90	8.93	8.70	11.88	12.29
Hydrogen	2.35*	2.35*	1.77*	1.77*	1.71*	1.82*
Oxygen	19.30	19.80	15.36	15.29	16.06	17.01
BALANCE (Out/In)						
Total Material	0.988	0.945	0.887	0.919	0.919	0.950
Nitrogen	0.949	0.831	0.757	0.818	0.836	0.848
Hydrogen	1.000	1.000	1.000	1.000	1.000	1.000
Oxygen	0.999	0.981	0.940	0.956	0.965	0.957

* By difference

Table A.1

STEADY STATE MATERIAL BALANCE

HIGHVALE COAL

Run No.	87	88	89	91
Press., atm	9.3	8.3	14.4	8.1
Temp., C	709	704	747	815

INPUT RATE (kg/hr)

By Material:

Coal (as rec.)	7.40	8.68	8.22	6.30
Air	15.91	17.35	16.92	18.24
Added Steam	11.82	8.30	24.23	4.72
Added N ₂	2.00	1.85	1.83	4.68
	=====	=====	=====	=====
Total Material In	37.13	36.18	51.20	33.94

By Element:

Nitrogen	14.18	15.13	14.78	18.64
Hydrogen	1.71	1.38	3.13	0.86
Oxygen	16.47	14.06	27.98	10.37

OUTPUT RATE (kg/hr)

By Material:

Dry Unreacted Coal	0.52	1.13	0.00	0.00
Dry Product Gas	22.53	23.80	28.48	26.86
Excess Steam	9.80*	6.66*	20.95	3.82
Ash in Reacted Coal	0.80	0.87	1.01	0.75
	=====	=====	=====	=====
Total Material Out	33.65	32.46	50.44	31.43

By Element:

Nitrogen	11.38	12.35	14.40	17.08
Hydrogen	1.71*	1.38*	3.13*	1.09
Oxygen	15.86	13.20	27.49	10.68

BALANCE (Out/In)

Total Material	0.906	0.897	0.985	0.926
Nitrogen	0.802	0.816	0.974	0.917
Hydrogen	1.000	1.000	1.000	1.262
Oxygen	0.963	0.939	0.983	1.030

* By difference

Table A.2

STEADY STATE MATERIAL BALANCE

COAL VALLEY COAL

Run No.	92	93	94	95	96
Press., atm	8.9	9.3	9.0	9.3	8.9
Temp., C	781	787	839	812	818
INPUT RATE (kg/hr)					
By Material:					
Coal (as rec.)	7.46	5.65	6.27	4.56	5.14
Air	12.38	16.88	17.19	16.68	15.89
Added Steam	10.85	22.33	9.10	8.27	15.71
Added N ₂	1.81	1.75	1.78	1.71	1.92
	=====	=====	=====	=====	=====
Total Material In	32.50	46.61	34.34	31.22	38.66
By Element:					
Nitrogen	11.28	14.68	14.95	14.48	14.09
Hydrogen	1.56	2.75	1.31	1.14	1.99
Oxygen	13.97	24.89	13.32	12.14	18.67
OUTPUT RATE (kg/hr)					
By Material:					
Dry Unreacted Coal	3.19	1.93	1.75	0.67	1.10
Dry Product Gas	17.47	22.75	22.43	21.27	20.90
Excess Steam	6.50	22.36	6.73	9.30	13.97
Ash in Reacted Coal	0.43	0.38	0.46	0.41	0.42
	=====	=====	=====	=====	=====
Total Material Out	27.58	47.42	31.37	31.64	36.39
By Element:					
Nitrogen	9.48	15.15	13.81	13.75	12.73
Hydrogen	1.39	3.06	1.39	1.49	2.10
Oxygen	12.13	26.25	12.73	14.21	18.91
BALANCE (Out/In)					
Total Material	0.849	1.017	0.913	1.014	0.941
Nitrogen	0.840	1.032	0.924	0.950	0.904
Hydrogen	0.889	1.111	1.063	1.313	1.055
Oxygen	0.869	1.054	0.955	1.171	1.013

Table A.2

STEADY STATE MATERIAL BALANCE

COAL VALLEY COAL

Run No.	97	98	99	100	101
Press., atm	14.2	5.2	9.0	9.0	8.8
Temp., C	842	811	881	845	903
INPUT RATE (kg/hr)					
By Material:					
Coal (as rec.)	7.10	7.92	5.72	6.56	6.71
Air or Oxygen	17.91	14.83	4.15	3.87	4.88
Added Steam	26.67	11.02	26.12	23.61	24.12
Added N ₂	1.67	1.79	1.92	2.23	2.42
	=====	=====	=====	=====	=====
Total Material In	53.35	35.56	37.91	36.27	38.13
By Element:					
Nitrogen	15.39	13.15	1.92	2.23	2.42
Hydrogen	3.30	1.60	3.18	2.94	3.00
Oxygen	29.26	14.79	28.47	26.11	27.60
OUTPUT RATE (kg/hr)					
By Material:					
Dry Unreacted Coal	2.05	3.52	0.90	1.42	0.43
Dry Product Gas	26.55	21.68	11.82	12.82	15.94
Excess Steam	21.23	10.11	24.56	21.27*	18.55
Ash in Reacted Coal	0.52	0.44	0.50	0.53	0.66
	=====	=====	=====	=====	=====
Total Material Out	50.35	35.75	37.78	36.04	35.58
By Element:					
Nitrogen	15.92	13.45	2.00	2.23	2.96
Hydrogen	3.05	1.85	3.28	2.94*	2.70
Oxygen	27.47	15.71	28.96	26.11	25.86
BALANCE (Out/In)					
Total Material	0.944	1.005	0.997	0.994	0.933
Nitrogen	1.035	1.023	1.042	1.160	1.222
Hydrogen	0.923	1.154	1.033	1.000	0.901
Oxygen	0.939	1.063	1.017	0.980	0.937

* By difference

Table A.3

STEADY STATE MATERIAL BALANCE

BYRON CREEK COAL

Run No.	148	149	151	152	153	161
Pressure, Atm	4.5	4.1	4.3	4.6	4.6	6.3
Temperature, C	839	813	828	839	852	899
INPUT RATE (kg/h)						
By Material:						
Coal (as rec.)	3.17	3.77	3.95	4.49	4.73	3.21
Oxidant	14.73	15.36	15.02	17.28	19.55	19.58
Added Steam	14.97	12.61	13.76	13.50	12.24	15.78
Added Nitrogen	0.77	0.75	0.57	0.58	0.58	0.59
	=====	=====	=====	=====	=====	=====
Total Material In	33.64	32.49	33.30	35.85	37.10	39.16
By Element:						
Nitrogen	12.04	12.51	12.07	13.81	15.54	14.98
Hydrogen	1.81	1.57	1.71	1.70	1.58	1.90
Oxygen	16.98	15.07	16.03	16.36	15.79	19.43
OUTPUT RATE (kg/h)						
By Material:						
Dry Unreacted Coal	0.19	1.03	1.19	1.28	1.37	0.01
Dry Product Gas	17.70	17.41	16.90	19.86	21.27	22.68
Excess Steam	13.97	14.24	14.92	15.06	12.92	12.56
Ash in Reacted Coal	0.37	0.34	0.35	0.40	0.42	0.40
	=====	=====	=====	=====	=====	=====
Total Material Out	32.23	33.02	33.36	36.60	35.98	35.65
By Element:						
Nitrogen	11.34	11.56	11.10	12.94	14.08	14.93
Hydrogen	1.79	1.86	1.98	2.05	1.83	1.62
Oxygen	17.43	17.37	17.87	18.89	17.18	17.63
BALANCE (Out/In)						
Total Material	0.958	1.016	1.001	1.021	0.970	0.911
Nitrogen	0.942	0.924	0.920	0.937	0.906	0.997
Hydrogen	0.992	1.184	1.157	1.200	1.160	0.850
Oxygen	1.027	1.153	1.115	1.155	1.088	0.907

Table A.4

STEADY STATE MATERIAL BALANCE

PRINCE HUB COAL

Run No.	134	138	139	140	162	164
Pressure, Atm	4.2	5.5	6.0	4.8	5.3	5.3
Temperature, C	881	830	846	863	887	889

INPUT RATE (kg/h)

By Material:

Coal (as rec.)	1.56	2.95	2.87	3.87	2.53	2.64
Oxidant	12.06	18.25	23.98	18.86	14.09	14.93
Added Steam	10.47	18.89	18.37	16.52	14.72	12.10
Added Nitrogen	1.45	0.83	1.06	1.14	0.46	0.56
	=====	=====	=====	=====	=====	=====
Total Material In	25.54	40.92	46.28	40.39	31.80	30.23

By Element:

Nitrogen	10.17	14.80	19.42	15.57	10.73	11.99
Hydrogen	1.24	2.25	2.19	2.03	1.76	1.48
Oxygen	12.89	21.51	22.39	19.69	17.28	14.66

OUTPUT RATE (kg/h)

By Material:

Dry Unreacted Coal	0.15	0.68	0.22	0.67	0.28	0.34
Dry Product Gas	12.00	18.32	24.45	22.41	16.17	16.82
Excess Steam	11.62	17.65	20.21	17.83	20.48	13.75
Ash in Reacted Coal	0.12	0.20	0.23	0.28	0.20	0.20
	=====	=====	=====	=====	=====	=====
Total Material Out	23.89	36.85	45.11	41.19	37.13	31.11

By Element:

Nitrogen	8.70	13.45	18.37	15.89	11.19	11.96
Hydrogen	1.40	2.19	2.44	2.29	2.43	1.72
Oxygen	13.39	20.08	23.54	21.36	22.58	16.45

BALANCE (Out/In)

Total Material	0.935	0.900	0.975	1.020	1.168	1.029
Nitrogen	0.856	0.908	0.946	1.021	1.043	0.998
Hydrogen	1.128	0.975	1.115	1.131	1.381	1.162
Oxygen	1.039	0.933	1.051	1.085	1.307	1.123

Table A.4 (Cont'd)

STEADY STATE MATERIAL BALANCE

PRINCE HUB COAL

Run No.	169
Pressure, Atm	4.0
Temperature, C	854

INPUT RATE (kg/h)

By Material:

Coal (as rec.)	2.78
Oxidant	12.88
Added Steam	11.52
Added Nitrogen	0.39

=====

Total Material In	27.57
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By Element:

Nitrogen	9.82
Hydrogen	1.42
Oxygen	14.11

OUTPUT RATE (kg/h)

By Material:

Dry Unreacted Coal	0.29
Dry Product Gas	14.82
Excess Steam	17.99
Ash in Reacted Coal	0.22

=====

Total Material Out	33.32
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By Element:

Nitrogen	9.65
Hydrogen	2.24
Oxygen	20.25

BALANCE (Out/In)

Total Material	1.208
Nitrogen	0.983
Hydrogen	1.576
Oxygen	1.435

Table A.5

STEADY STATE MATERIAL BALANCE

PITTSBURGH COAL

Run No.	170	177	184	187
Pressure, Atm	3.8	4.1	4.5	5.0
Temperature, C	814	907	865	868
INPUT RATE (kg/h)				
By Material:				
Coal (as rec.)	3.12	2.81	2.74	2.62
Oxidant	8.87	14.70	12.05	12.94
Added Steam	9.49	9.95	9.56	12.34
Added Nitrogen	0.40	0.38	0	0.33
	=====	=====	=====	=====
Total Material In	21.88	27.84	24.35	28.23
By Element:				
Nitrogen	7.19	10.96	9.22	10.23
Hydrogen	1.21	1.25	1.20	1.50
Oxygen	10.80	13.22	11.57	14.24
OUTPUT RATE (kg/h)				
By Material:				
Dry Unreacted Coal	1.31	0.69	0.22	0.45
Dry Product Gas	11.04	15.59	13.77	14.25
Excess Steam	9.27	10.58	12.45	12.86
Ash in Reacted Coal	0.15	0.17	0.21	0.18
	=====	=====	=====	=====
Total Material Out	21.77	27.03	26.65	27.74
By Element:				
Nitrogen	7.27	10.56	8.30	9.58
Hydrogen	1.21*	1.25*	1.63	1.60
Oxygen	10.70*	12.92*	15.35	15.30
BALANCE (Out/In)				
Total Material	0.995	0.971	1.095	0.982
Nitrogen	1.011	0.963	0.901	0.936
Hydrogen	1.000	1.000	1.360	1.064
Oxygen	0.991	0.978	1.327	1.074

* By difference



OVERALL MASS BALANCE

RUN NO. 75

INPUT	C	H	N	O	S	Ash	Total
Dry Coal	6.939	0.438	0.109	1.828	0.021	1.592	10.928
Steam		1.170		9.361			10.531
Oxidant			26.712	8.189			34.901
Nitrogen			3.364				3.364
TOTAL	6.939	1.608	30.185	19.378	0.021	1.592	59.722
OUTPUT	C	H	N	O	S	Ash	Total
Dry Gas	6.690	0.854	30.518	12.254	0.000		50.317
Steam (by diff.)		0.715		5.717			6.431
Reactor Bed	0.039					0.397	0.436
Char Overflow	0.000					0.000	0.000
Fine Ash	0.189					0.151	0.340
Coarse Ash	0.243					0.491	0.734
TOTAL	7.162	1.569	30.518	17.970	0.000	1.038	58.258
Out/In O	1.032	0.975	1.011	0.927	0.000	0.652	0.975

OVERALL MASS BALANCE

RUN NO. 83

INPUT	C	H	N	O	S	Ash	Total
Dry Coal	5.592	0.353	0.087	1.473	0.017	1.283	8.807
Steam		4.274		34.190			38.464
Oxidant			14.946	4.582			19.527
Nitrogen			4.291				4.291
TOTAL	5.592	4.627	19.324	40.245	0.017	1.283	71.088
OUTPUT	C	H	N	O	S	Ash	Total
Dry Gas	3.587	0.638	16.568	7.405	0.000		28.198
Steam (by diff.)		3.866		30.931			34.798
Reactor Bed	0.629					0.291	0.920
Char Overflow	0.115					0.030	0.145
Fine Ash	0.137					0.076	0.214
Coarse Ash	0.145					0.053	0.198
TOTAL	4.612	4.504	16.568	38.336	0.000	0.451	64.472
Out/In O	0.825	0.973	0.857	0.953	0.000	0.351	0.907

OVERALL MASS BALANCE

RUN NO. 85

INPUT	C	H	N	O	S	Ash	Total
Dry Coal	3.728	0.235	0.058	0.982	0.012	0.855	5.872
Steam		2.365		18.924			21.289
Oxidant			19.553	5.994			25.547
Nitrogen			2.936				2.936
TOTAL	3.728	2.601	22.547	25.900	0.012	0.855	55.643
OUTPUT	C	H	N	O	S	Ash	Total
Dry Gas	3.809	0.614	18.812	7.858	0.000		31.094
Steam (by diff.)		1.978		15.827			17.805
Reactor Bed	0.072					0.287	0.359
Char Overflow	0.007					0.001	0.008
Fine Ash	0.155					0.073	0.228
Coarse Ash	0.160					0.159	0.318
TOTAL	4.203	2.593	18.812	23.685	0.000	0.520	49.813
Out/In O	1.127	0.997	0.834	0.914	0.000	0.608	0.895

OVERALL MASS BALANCE

RUN NO. 86

INPUT	C	H	N	O	S	Ash	Total
Dry Coal	4.557	0.288	0.071	1.200	0.014	1.045	7.176
Steam		2.740		21.923			24.663
Oxidant			20.662	6.334			26.996
Nitrogen			3.241				3.241
TOTAL	4.557	3.028	23.974	29.457	0.014	1.045	62.075
OUTPUT	C	H	N	O	S	Ash	Total
Dry Gas	4.222	0.690	20.276	8.666	0.000		33.853
Steam (by diff.)		2.302		18.419			20.722
Reactor Bed	0.059					0.275	0.334
Char Overflow	0.011					0.016	0.028
Fine Ash	0.193					0.080	0.273
Coarse Ash	0.217					0.216	0.433
TOTAL	4.703	2.992	20.276	27.085	0.000	0.588	55.643
Out/In O	1.032	0.988	0.846	0.919	0.000	0.562	0.896

OVERALL MASS BALANCE

RUN NO. 87

INPUT	C	H	N	O	S	Ash	Total
Dry Coal	7.663	0.484	0.120	2.019	0.024	1.758	12.069
Steam		2.907		23.252			26.159
Oxidant			24.151	7.404			31.555
Nitrogen			3.971				3.971
TOTAL	7.663	3.390	28.242	32.675	0.024	1.758	73.752
OUTPUT	C	H	N	O	S	Ash	Total
Dry Gas	5.781	0.966	22.562	11.655	0.000		40.965
Steam (by diff.)		2.285		18.283			20.568
Reactor Bed	1.344					1.156	2.500
Char Overflow	0.014					0.005	0.018
Fine Ash	0.160					0.094	0.253
Coarse Ash	0.187					0.160	0.347
TOTAL	7.486	3.251	22.562	29.938	0.000	1.414	64.652
Out/In O	0.977	0.959	0.799	0.916	0.000	0.804	0.877

OVERALL MASS BALANCE

RUN NO. 88

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	7.042	0.445	0.110	1.855	0.022	1.616	11.091
Steam		1.724		13.792			15.516
Oxidant			20.798	6.376			27.174
Nitrogen			2.905				2.905
TOTAL	7.042	2.169	23.813	22.023	0.022	1.616	56.684
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	4.408	0.683	19.341	8.280	0.000		32.711
Steam (by diff.)		1.303		10.426			11.729
Reactor Bed	1.450					0.933	2.383
Char Overflow	0.209					0.048	0.257
Fine Ash	0.036					0.076	0.113
Coarse Ash	0.208					0.399	0.607
TOTAL	6.311	1.987	19.341	18.705	0.000	1.456	47.800
Out/In O	0.896	0.916	0.812	0.849	0.000	0.901	0.843

OVERALL MASS BALANCE

RUN NO. 89

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	6.110	0.386	0.096	1.610	0.019	1.402	9.623
Steam		4.387		35.098			39.485
Oxidant			19.856	6.087			25.942
Nitrogen			2.809				2.809
TOTAL	6.110	4.773	22.760	42.794	0.019	1.402	77.858
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	4.750	0.861	22.085	9.642	0.000		37.337
Steam (by diff.)		3.810		30.478			34.288
Reactor Bed	0.053					0.496	0.546
Char Overflow	0.072					0.018	0.090
Fine Ash	0.420					0.250	0.671
Coarse Ash	0.524					0.128	0.651
TOTAL	5.819	4.670	22.085	40.120	0.000	0.891	73.585
Out/In O	0.952	0.978	0.970	0.938	0.000	0.636	0.945

OVERALL MASS BALANCE

RUN NO. 90

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	9.532	0.602	0.149	2.511	0.029	2.187	15.013
Steam		4.768		38.142			42.909
Oxidant			0.000	7.047			7.047
Nitrogen			3.377				3.377
TOTAL	9.532	5.370	3.526	47.699	0.029	2.187	68.344
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	6.997	1.085	3.177	15.771	0.000		27.031
Excess Steam		4.055		32.438			36.492
Reactor Bed	1.510					0.670	2.180
Char Overflow	0.133					0.037	0.170
Fine Ash	0.271					0.223	0.495
Coarse Ash	0.433					0.154	0.587
TOTAL	9.345	5.139	3.177	48.209	0.000	1.084	66.955
Out/In	0.980	0.957	0.901	1.011	0.000	0.496	0.980

OVERALL MASS BALANCE

RUN NO. 91

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	5.458	0.345	0.085	1.438	0.017	1.252	8.595
Steam		0.986		7.889			8.875
Oxidant			21.056	6.455			27.510
Nitrogen			7.054				7.054
TOTAL	5.458	1.331	28.196	15.781	0.017	1.252	52.034
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	4.526	0.679	25.767	8.324	0.000		39.295
Excess Steam		0.668		5.345			6.014
Reactor Bed	0.280					0.447	0.727
Char Overflow	0.026					0.007	0.034
Fine Ash	0.278					0.354	0.632
Coarse Ash	0.210					0.089	0.298
TOTAL	5.319	1.347	25.767	13.669	0.000	0.897	46.999
Out/In	0.975	1.012	0.914	0.866	0.000	0.716	0.903

Bed Carbon, Initial Weight, kg = 0.535

Bed Carbon, Final Weight, kg = 0.280

OVERALL MASS BALANCE

RUN NO. 92

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	5.345	0.325	0.072	1.018	0.013	0.877	7.642
Steam		1.220		9.756			10.976
Oxidant			9.109	2.792			11.902
Nitrogen			1.740				1.740
TOTAL	5.345	1.545	10.921	13.567	0.013	0.877	32.267
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.051	0.319	9.120	3.945	0.000		15.435
Excess Steam		0.787		6.300			7.087
Reactor Bed	1.268					0.507	1.775
Char Overflow	0.000					0.000	0.000
Fine Ash	0.773					0.146	0.920
Coarse Ash	0.000					0.000	0.000
TOTAL	4.093	1.107	9.120	10.245	0.000	0.654	25.218
Out/In	0.766	0.717	0.835	0.755	0.000	0.746	0.782

Bed Carbon, Initial Weight, kg = 0.700

Bed Carbon, Final Weight, kg = 1.268

OVERALL MASS BALANCE

RUN NO. 93

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	4.844	0.295	0.065	0.923	0.012	0.795	6.927
Steam		2.921		23.371			26.292
Oxidant			14.926	4.575			19.501
Nitrogen			2.020				2.020
TOTAL	4.844	3.216	17.011	28.869	0.012	0.795	54.747
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.231	0.329	17.492	4.829	0.000		24.881
Excess Steam		2.878		23.022			25.900
Reactor Bed	0.226					0.344	0.570
Char Overflow	0.127					0.041	0.168
Fine Ash	0.625					0.343	0.968
Coarse Ash	0.186					0.050	0.236
TOTAL	3.395	3.207	17.492	27.851	0.000	0.778	52.724
Out/In	0.701	0.997	1.028	0.965	0.000	0.979	0.963

Bed Carbon, Initial Weight, kg = 0.630
 Bed Carbon, Final Weight, kg = 0.226

OVERALL MASS BALANCE

RUN NO. 94

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	4.220	0.257	0.057	0.804	0.010	0.692	6.038
Steam		1.082		8.655			9.737
Oxidant			13.378	4.101			17.479
Nitrogen			1.813				1.813
TOTAL	4.220	1.339	15.247	13.560	0.010	0.692	35.069
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.237	0.332	14.042	4.251	0.000		20.862
Excess Steam		0.831		6.650			7.481
Reactor Bed	0.539					0.590	1.129
Char Overflow	1.142					0.175	1.316
Fine Ash	0.210					0.070	0.281
Coarse Ash	0.218					0.032	0.250
TOTAL	4.346	1.163	14.042	10.901	0.000	0.868	31.321
Out/In	1.030	0.869	0.921	0.804	0.000	1.254	0.893

Bed Carbon, Initial Weight, kg = 0.450
 Bed Carbon, Final Weight, kg = 0.539
 0

OVERALL MASS BALANCE

RUN NO. 95

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	3.600	0.219	0.048	0.686	0.009	0.591	5.148
Steam		1.101		8.808			9.909
Oxidant			14.685	4.502			19.187
Nitrogen			1.963				1.963
TOTAL	3.600	1.320	16.696	13.995	0.009	0.591	36.211
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.438	0.281	15.816	4.673	0.000		23.208
Excess Steam		1.175		9.403			10.578
Reactor Bed	0.192					0.462	0.654
Char Overflow	0.062					0.012	0.074
Fine Ash	0.049					0.034	0.083
Coarse Ash	0.075					0.081	0.156
TOTAL	2.816	1.456	15.816	14.075	0.000	0.589	34.753
Out/In	0.782	1.103	0.947	1.006	0.000	0.997	0.960

Bed Carbon, Initial Weight, kg = 0.452

Bed Carbon, Final Weight, kg = 0.192

0

OVERALL MASS BALANCE

RUN NO. 96

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	3.818	0.232	0.051	0.727	0.009	0.626	5.460
Steam		1.729		13.833			15.562
Oxidant			11.759	3.605			15.364
Nitrogen			1.855				1.855
TOTAL	3.818	1.961	13.666	18.165	0.009	0.626	38.246
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.164	0.305	12.308	4.475	0.000		19.252
Excess Steam		1.528		12.221			13.746
Reactor Bed	0.313					0.184	0.497
Char Overflow	0.290					0.078	0.367
Fine Ash	0.066					0.063	0.129
Coarse Ash	0.137					0.116	0.253
TOTAL	2.970	1.832	12.308	16.696	0.000	0.440	34.246
Out/In	0.778	0.934	0.901	0.919	0.000	0.703	0.895

Bed Carbon, Initial Weight, kg = 0.574

Bed Carbon, Final Weight, kg = 0.313

OVERALL MASS BALANCE

RUN NO. 97

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	4.883	0.297	0.066	0.930	0.012	0.801	6.983
Steam		2.872		22.976			25.848
Oxidant			13.025	3.993			17.018
Nitrogen			1.590				1.590
TOTAL	4.883	3.169	14.681	27.899	0.012	0.801	51.446
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.578	0.354	15.123	5.756	0.000		23.812
Excess Steam		2.329		18.635			20.965
Reactor Bed	0.720					0.197	0.917
Char Overflow	0.087					0.016	0.103
Fine Ash	0.137					0.113	0.250
Coarse Ash	0.154					0.100	0.254
TOTAL	3.677	2.683	15.123	24.392	0.000	0.427	46.302
Out/In	0.753	0.847	1.030	0.874	0.000	0.533	0.900

Bed Carbon, Initial Weight, kg = 0.493

Bed Carbon, Final Weight, kg = 0.720

O

OVERALL MASS BALANCE

RUN NO. 98

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	7.490	0.456	0.101	1.427	0.019	1.229	10.710
Steam		1.722		13.773			15.494
Oxidant			15.138	4.641			19.779
Nitrogen			2.391				2.391
TOTAL	7.490	2.177	17.630	19.840	0.019	1.229	48.384
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	3.249	0.526	17.939	6.302	0.000		28.015
Excess Steam		1.517		12.132			13.649
Reactor Bed	0.923					0.451	1.374
Char Overflow	0.000					0.000	0.000
Fine Ash	0.505					0.239	0.744
Coarse Ash	0.456					0.208	0.664
TOTAL	5.133	2.042	17.939	18.434	0.000	0.898	44.445
Out/In	0.685	0.938	1.018	0.929	0.000	0.731	0.919

Bed Carbon, Initial Weight, kg = 0.615

Bed Carbon, Final Weight, kg = 0.923

O

OVERALL MASS BALANCE

RUN NO. 99

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	5.702	0.347	0.077	1.086	0.014	0.935	8.153
Steam		2.459		19.675			22.135
Oxidant			0.000	3.459			3.459
Nitrogen			1.598				1.598
TOTAL	5.702	2.806	1.675	24.221	0.014	0.935	35.353
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	1.916	0.263	1.665	3.961	0.000		7.805
Excess Steam		2.320		18.563			20.883
Reactor Bed	0.000					0.000	0.000
Char Overflow	0.192					0.075	0.267
Fine Ash	0.084					0.090	0.174
Coarse Ash	0.291					0.121	0.412
TOTAL	2.483	2.583	1.665	22.523	0.000	0.286	29.541
Out/In	0.436	0.921	0.994	0.930	0.000	0.306	0.836

Bed Carbon, Initial Weight, kg = 0.437
 Bed Carbon, Final Weight, kg = 0.000

OVERALL MASS BALANCE

RUN NO. 100

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	6.045	0.368	0.081	1.151	0.015	0.992	8.643
Steam		3.170		25.361			28.532
Oxidant			0.000	4.581			4.581
Nitrogen			2.635				2.635
TOTAL	6.045	3.538	2.717	31.094	0.015	0.992	44.399
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	3.296	0.512	3.057	6.603	0.000		13.467
Steam (by diff.)		2.849		22.789			25.638
Reactor Bed	0.066					0.271	0.336
Char Overflow	0.289					0.075	0.364
Fine Ash	0.223					0.148	0.371
Coarse Ash	0.000					0.000	0.000
TOTAL	3.873	3.361	3.057	29.392	0.000	0.494	40.176
Out/In	0.641	0.950	1.125	0.945	0.000	0.496	0.905

Bed Carbon, Initial Weight, kg = 0.487
 Bed Carbon, Final Weight, kg = 0.066

OVERALL MASS BALANCE

RUN NO. 148

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	3.821	0.229	0.061	0.388	0.018	1.378	5.895
Steam		2.438		19.508			21.946
Oxidant			16.493	5.056			21.549
Nitrogen			1.119				1.119
TOTAL	3.821	2.667	17.673	24.951	0.018	1.378	50.509
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.872	0.134	16.586	5.229	0.000		24.821
Excess Steam		2.289		18.312			20.600
Reactor Bed	0.012					0.983	0.995
Char Overflow	0.000					0.000	0.000
Fine Ash	0.311					0.248	0.559
Coarse Ash	0.072					0.079	0.151
TOTAL	3.266	2.423	16.586	23.541	0.000	1.310	47.126
Out/In	0.855	0.908	0.939	0.943	0.000	0.951	0.933

Bed Carbon, Initial Weight, kg = 0.745
 Bed Carbon, Final Weight, kg = 0.012

OVERALL MASS BALANCE

RUN NO. 149

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	4.202	0.251	0.067	0.417	0.020	1.443	6.400
Steam		2.060		16.480			18.540
Oxidant			17.215	5.277			22.493
Nitrogen			1.101				1.101
TOTAL	4.202	2.311	18.384	22.174	0.020	1.443	48.533
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.638	0.142	16.932	4.816	0.000		24.530
Excess Steam		2.288		18.300			20.588
Reactor Bed	0.268					0.727	0.995
Char Overflow	0.080					0.030	0.110
Fine Ash	0.283					0.267	0.550
Coarse Ash	0.335					0.236	0.571
TOTAL	3.604	2.430	16.932	23.119	0.000	1.260	47.344
Out/In	0.856	1.051	0.921	1.043	0.000	0.873	0.975

Bed Carbon, Initial Weight, kg = 0.745
 Bed Carbon, Final Weight, kg = 0.268
 0

OVERALL MASS BALANCE

RUN NO. 151

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	4.435	0.265	0.071	0.434	0.021	0.782	6.009
Steam		2.546		20.367			22.913
Oxidant			19.079	5.849			24.927
Nitrogen			0.951				0.951
TOTAL	4.435	2.811	20.101	26.650	0.021	0.782	54.800
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.972	0.206	18.422	5.238	0.000		26.638
Excess Steam		2.724		21.792			24.516
Reactor Bed	0.601					0.224	0.824
Char Overflow	0.000					0.000	0.000
Fine Ash	0.431					0.190	0.620
Coarse Ash	0.361					0.201	0.562
TOTAL	4.364	2.930	18.422	27.030	0.000	0.414	53.150
Out/In	0.984	1.043	0.916	1.014	0.000	0.785	0.974

Bed Carbon, Initial Weight, kg = 0.745
 Bed Carbon, Final Weight, kg = 0.601

OVERALL MASS BALANCE

RUN NO. 152

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	4.329	0.259	0.069	0.426	0.021	1.264	6.369
Steam		1.856		14.847			16.703
Oxidant			16.303	4.998			21.300
Nitrogen			0.714				0.714
TOTAL	4.329	2.115	17.086	20.271	0.021	1.264	45.086
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.532	0.185	15.945	4.662	0.000		23.324
Excess Steam		2.034		16.273			18.307
Reactor Bed	0.220					0.428	0.648
Char Overflow	0.367					0.122	0.489
Fine Ash	0.358					0.294	0.652
Coarse Ash	0.130					0.086	0.216
TOTAL	3.606	2.219	15.945	20.934	0.000	0.930	43.635
Out/In	0.833	1.049	0.933	1.033	0.000	0.736	0.968

Bed Carbon, Initial Weight, kg = 0.745
 Bed Carbon, Final Weight, kg = 0.220
 0

OVERALL MASS BALANCE

RUN NO. 153

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	4.118	0.246	0.066	0.410	0.019	1.228	6.088
Steam		1.596		12.769			14.366
Oxidant			17.476	5.357			22.833
Nitrogen			0.676				0.676
TOTAL	4.118	1.842	18.218	18.537	0.019	1.228	43.963
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.493	0.184	16.443	4.519	0.000		23.640
Excess Steam		1.666		13.325			14.990
Reactor Bed	0.635					0.637	1.273
Char Overflow	0.299					0.248	0.547
Fine Ash	0.215					0.195	0.411
Coarse Ash	0.348					0.148	0.495
TOTAL	3.991	1.850	16.443	17.844	0.000	1.228	41.356
Out/In	0.969	1.004	0.903	0.963	0.000	1.000	0.941

Bed Carbon, Initial Weight, kg = 0.745
 Bed Carbon, Final Weight, kg = 0.635

OVERALL MASS BALANCE

RUN NO. 161

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	2.720	0.163	0.044	0.304	0.013	0.992	4.236
Steam		2.170		17.356			19.526
Oxidant			17.756	5.443			23.199
Nitrogen			0.729				0.729
TOTAL	2.720	2.333	18.529	23.103	0.013	0.992	47.687
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.440	0.066	18.427	5.441	0.000		26.374
Excess Steam		1.798		14.386			16.185
Reactor Bed	0.067					0.593	0.660
Char Overflow	0.000					0.000	0.000
Fine Ash	0.358					0.304	0.662
Coarse Ash	0.084					0.076	0.160
TOTAL	2.949	1.864	18.427	19.828	0.000	0.973	44.041
Out/In	1.084	0.799	0.995	0.858	0.000	0.981	0.923

Bed Carbon, Initial Weight, kg = 0.745
 Bed Carbon, Final Weight, kg = 0.067
 0

OVERALL MASS BALANCE

RUN NO. 134

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	2.868	0.187	0.055	0.535	0.105	0.997	4.746
Steam		2.893		23.142			26.034
Oxidant			22.804	6.990			29.794
Nitrogen			3.576				3.576
TOTAL	2.868	3.079	26.434	30.667	0.105	0.997	64.151
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.006	0.020	21.480	5.028	0.000		28.535
Excess Steam		3.149		25.189			28.338
Reactor Bed	0.023					0.730	0.753
Char Overflow	0.000					0.000	0.000
Fine Ash	0.047					0.050	0.097
Coarse Ash	0.058					0.082	0.140
TOTAL	2.135	3.169	21.480	30.218	0.000	0.861	57.864
Out/In	0.745	1.029	0.813	0.985	0.000	0.864	0.902

Bed Carbon, Initial Weight, kg = 1.002
 Bed Carbon, Final Weight, kg = 0.023

OVERALL MASS BALANCE

RUN NO. 138

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	3.172	0.207	0.060	0.585	0.119	1.037	5.180
Steam		3.992		31.936			35.928
Oxidant			26.391	8.090			34.481
Nitrogen			1.568				1.568
TOTAL	3.172	4.199	28.019	40.612	0.119	1.037	77.157
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.444	0.101	25.399	5.450	0.000		33.394
Excess Steam		3.742		29.939			33.681
Reactor Bed	0.214					0.611	0.825
Char Overflow	0.000					0.000	0.000
Fine Ash	0.009					0.014	0.023
Coarse Ash	0.058					0.113	0.171
TOTAL	2.726	3.843	25.399	35.388	0.000	0.737	68.094
Out/In	0.860	0.915	0.906	0.871	0.000	0.711	0.883

Bed Carbon, Initial Weight, kg = 1.002
 Bed Carbon, Final Weight, kg = 0.214
 0

OVERALL MASS BALANCE

RUN NO. 139

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	2.052	0.134	0.039	0.380	0.076	0.850	3.530
Steam		1.977		15.815			17.792
Oxidant			17.649	5.410			23.060
Nitrogen			1.020				1.020
TOTAL	2.052	2.111	18.709	21.605	0.076	0.850	45.402
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	1.403	0.011	17.663	3.426	0.000		22.502
Excess Steam		2.128		17.021			19.149
Reactor Bed	0.234					0.526	0.760
Char Overflow	0.000					0.000	0.000
Fine Ash	0.016					0.024	0.040
Coarse Ash	0.045					0.078	0.123
TOTAL	1.698	2.139	17.663	20.447	0.000	0.628	42.574
Out/In	0.828	1.013	0.944	0.946	0.000	0.739	0.938

Bed Carbon, Initial Weight, kg = 0.668

Bed Carbon, Final Weight, kg = 0.234

OVERALL MASS BALANCE

RUN NO. 140

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	2.924	0.193	0.055	0.524	0.117	0.965	4.778
Steam		2.166		17.329			19.495
Oxidant			18.856	5.167			22.024
Nitrogen			1.328				1.328
TOTAL	2.924	2.359	18.239	23.021	0.117	0.965	47.625
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	1.767	0.102	18.561	3.571	0.000		24.002
Excess Steam		2.272		18.176			20.448
Reactor Bed	0.075					0.749	0.824
Char Overflow	0.000					0.000	0.000
Fine Ash	0.160					0.114	0.274
Coarse Ash	0.172					0.074	0.247
TOTAL	2.174	2.374	18.561	21.747	0.000	0.938	45.795
Out/In	0.743	1.007	1.018	0.945	0.000	0.972	0.962

Bed Carbon, Initial Weight, kg = 0.668

Bed Carbon, Final Weight, kg = 0.075

0

OVERALL MASS BALANCE

RUN NO. 162

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	1.581	0.104	0.028	0.313	0.051	0.760	2.836
Steam		2.603		20.822			23.425
Oxidant			16.094	4.934			21.028
Nitrogen			0.723				0.723
TOTAL	1.581	2.707	16.844	26.068	0.051	0.760	48.011
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	2.017	0.027	17.550	4.705	0.000		24.299
Excess Steam		3.439		27.512			30.951
Reactor Bed	0.020					0.637	0.657
Char Overflow	0.000					0.000	0.000
Fine Ash	0.028					0.031	0.058
Coarse Ash	0.035					0.051	0.086
TOTAL	2.100	3.466	17.550	32.217	0.000	0.718	56.051
Out/In	1.328	1.281	1.042	1.236	0.000	0.946	1.167

Bed Carbon, Initial Weight, kg = 0.668
 Bed Carbon, Final Weight, kg = 0.020

OVERALL MASS BALANCE

RUN NO. 164

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	2.074	0.138	0.037	0.394	0.074	0.925	3.642
Steam		1.853		14.823			16.676
Oxidant			15.588	4.779			20.367
Nitrogen			0.770				0.770
TOTAL	2.074	1.990	16.395	19.996	0.074	0.925	41.455
OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	1.639	0.051	16.323	3.524	0.000		21.537
Excess Steam		2.035		16.283			18.318
Reactor Bed	0.520					0.093	0.613
Char Overflow	0.000					0.000	0.000
Fine Ash	0.128					0.011	0.139
Coarse Ash	0.051					0.040	0.091
TOTAL	2.338	2.086	16.323	19.807	0.000	0.144	40.699
Out/In	1.127	1.048	0.996	0.991	0.000	0.156	0.982

Bed Carbon, Initial Weight, kg = 0.668
 Bed Carbon, Final Weight, kg = 0.520
 □ run

OVERALL MASS BALANCE

RUN NO. 169

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	3.137	0.209	0.056	0.570	0.123	0.966	5.061
Steam		1.780		14.242			16.022
Oxidant			12.980	3.979			16.958
Nitrogen			0.533				0.533
TOTAL	3.137	1.989	13.568	18.791	0.123	0.966	38.574

OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	1.865	0.123	13.283	3.830	0.000		19.101
Excess Steam		2.575		20.601			23.176
Reactor Bed	0.331					0.212	0.542
Char Overflow	0.000					0.000	0.000
Fine Ash	0.282					0.160	0.442
Coarse Ash	0.039					0.043	0.083
TOTAL	2.517	2.698	13.283	24.431	0.000	0.415	43.345

Out/In	0.803	1.356	0.979	1.300	0.000	0.430	1.124
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Bed Carbon, Initial Weight, kg = 0.668
 Bed Carbon, Final Weight, kg = 0.331

OVERALL MASS BALANCE

RUN NO. 177

INPUT (kg)	C	H	N	O	S	Ash	Total
Dry Coal	1.846	0.120	0.032	0.268	0.063	0.867	3.198
Steam		1.066		8.524			9.590
Oxidant			10.137	3.108			13.245
Nitrogen			0.368				0.368
TOTAL	1.846	1.185	10.538	11.900	0.063	0.867	26.400

OUTPUT (kg)	C	H	N	O	S	Ash	Total
Dry Gas	1.141	0.020	10.122	2.567	0.000		13.850
Steam (by diff.)		1.066		8.524			9.590
Reactor Bed	0.577					0.181	0.758
Char Overflow	0.000					0.000	0.000
Fine Ash	0.008					0.153	0.161
Coarse Ash	0.012					0.019	0.030
TOTAL	1.738	1.086	10.122	11.091	0.000	0.353	24.389

Out/In	0.941	0.916	0.961	0.932	0.000	0.407	0.924
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Bed Carbon, Initial Weight, kg = 0.731
 Bed Carbon, Final Weight, kg = 0.577
 0

APPENDIX B

Test Results for Run TA75.

The results for Run TA75 are presented as a representative set of data for the series of gasification tests. In Run TA75 Highvale coal was gasified with air and steam at a pressure of 5 atmospheres and data at two operating temperatures were obtained. The computer output plots of pressure and temperature for the test are shown in Figures B.1 and B.2. The starting time shown in these plots is the beginning of data collection for the run which comes after a suitable heating-up period. The units shown in brackets on the axes indicate the intervals between graduation marks on the axes. The very small difference between the feed hopper pressure and the reactor pressure in Figure B.1 indicates that no upsets in coal feeding were experienced during the run. The rise in pressure following the introduction of coal comes from the increase in amount of the product gas resulting from the combustion and gasification reactions. After one hour on coal (at time = 70 min.) the coal and water rates were reduced. This resulted in a lower gas production rate and a slight drop in operating pressure. The changes in temperature are larger as seen in Figure B.2. Here the temperatures at two points in the reactor bed, 150 mm apart, are shown and the average of the two is taken as the reactor temperature. When air is injected, there is a sharp rise in temperature as combustion occurs and the system reached steady state at about 790 C after about 35 minutes on coal. Later, when the coal and steam rates were reduced, the temperature rose steadily and reached 900 C after about 40 minutes. Gas samples were withdrawn at intervals of about 18 minutes and analysed by a gas chromatograph. The individual gas analyses are shown in Table B.1. The average for G.C. samples numbers 1 and 2 was taken as the steady state composition for 790 C and, similarly, the average of sample numbers 5 and 6 for 900 C.

TEST RESULTS

RUN TA75

DRY GAS ANALYSIS

Gas Chromat. No.	1	2	3	4	5	6
Time on Coal (Min)	36	54	75	96	115	134
Composition, Vol. %						
H2	19.71	21.53	18.04	15.97	15.52	15.54
N2	51.41	48.13	50.81	54.82	55.73	56.54
CH4	1.77	1.76	1.49	1.44	1.51	1.49
CO	13.35	15.90	18.65	14.68	14.93	14.57
CO2	13.70	12.54	11.01	13.09	12.31	11.79
C2H6	0.06	0.14	0	0	0	0.06
HHV, kcal/m3	1182	1327	1255	1067	1067	1066
MJ/m3	4.95	5.56	5.25	4.47	4.47	4.46

FIGURE B.1

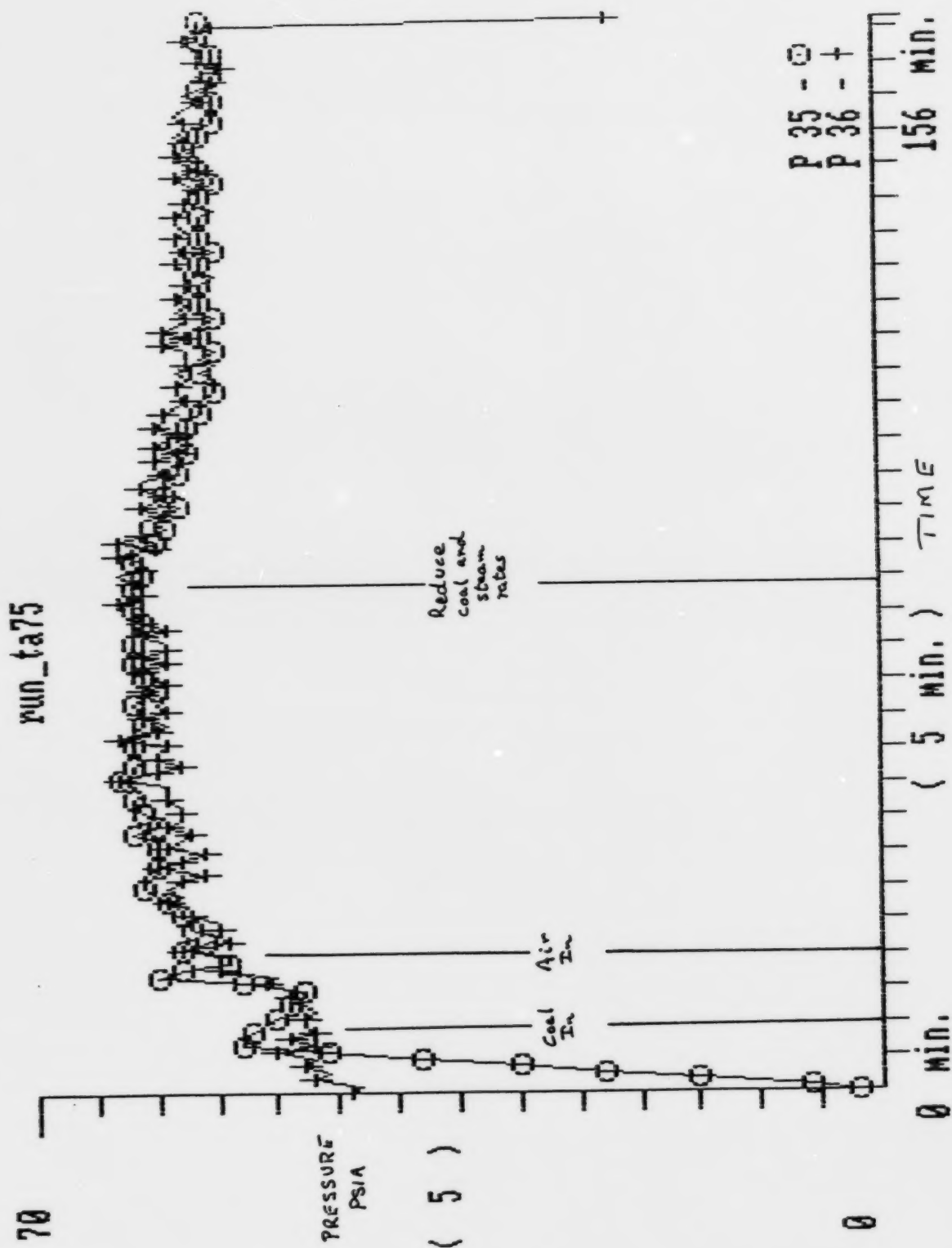
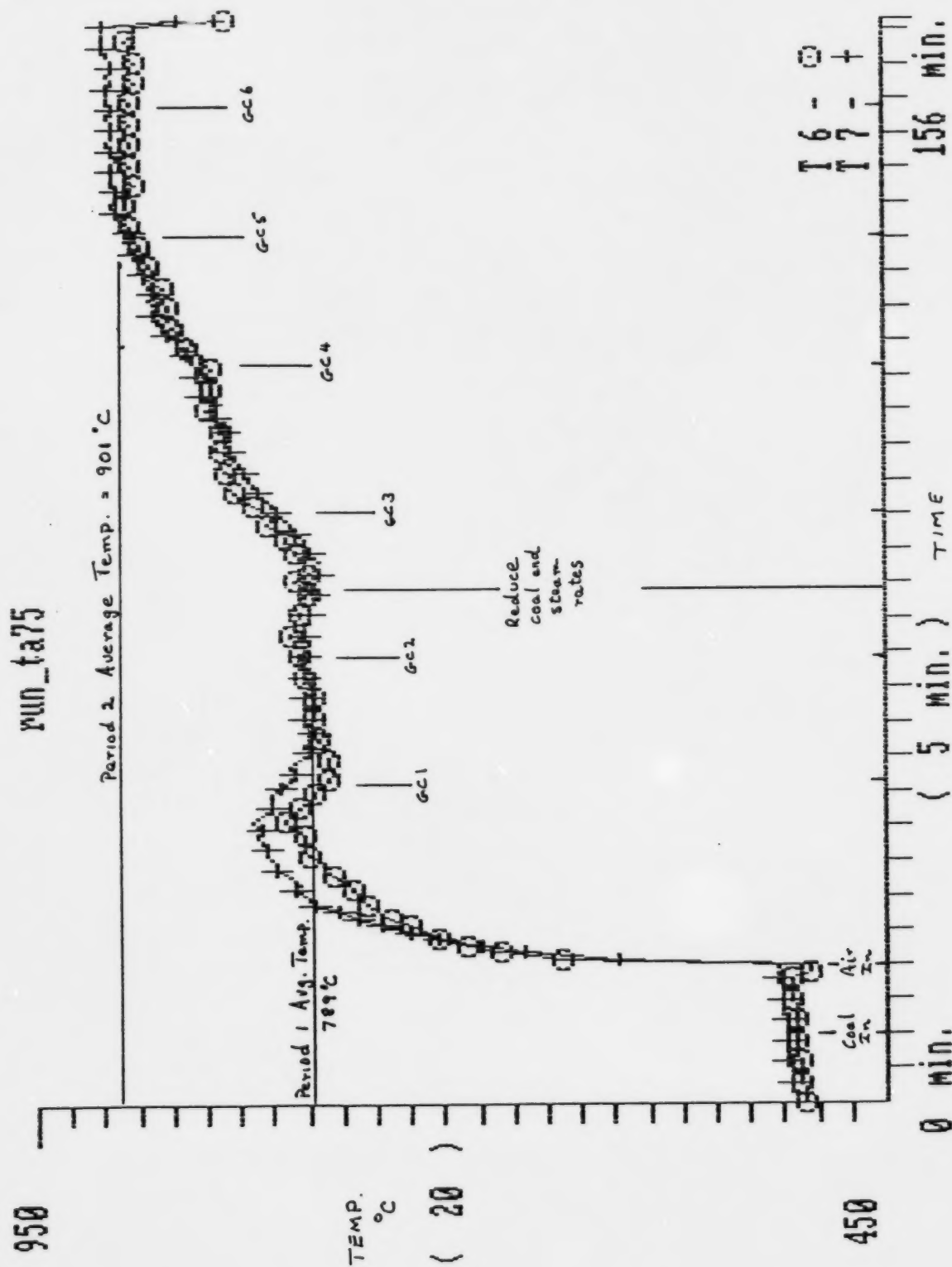


FIGURE B.2



Thermodynamic Equilibrium Model

Results of gas composition measurements were compared with predictions of an equilibrium model, in which the exit gas composition of the gasifier is determined solely by stoichiometric and thermodynamic constraints. Thus it is assumed that all feed oxygen is consumed, as was shown by Haji-Sulaiman et al., 1986, carbon conversion is given from the experimental measurements, and that the exit gases contain H_2 , CO , CO_2 , CH_4 , H_2O and N_2 , and are in water-gas shift and methanation equilibria at the average gasifier pressure and temperature. The model consists of a series of elemental mass balance equations for C, O, H, and N, the equilibrium equations of the water-gas shift and the methanation reactions, and Dalton's Law.

The equilibrium expressions for the water-gas shift and methanation reactions respectively are:

$$K_1 = \frac{(y_{H_2})(y_{CO_2})}{(y_{CO})(y_{H_2O})} \quad (4)$$

$$K_2 = \frac{(y_{CH_4})(y_{H_2O})}{(y_{CO})(y_{H_2})^3 p^2} \quad (5)$$

K_1 and K_2 are the corresponding equilibrium constants given by the following expressions (Kosky and Floess, 1980; Probststein and Hicks, 1982):

$$K_1 = 0.0265 \exp(3956/T_b)$$

$$K_2 = 6.538 \times 10^{-18} \exp(27020/T_b)$$

The elemental mass balance equations for H, O, C and N are respectively,

$$(2y_{\text{CH}_4} + y_{\text{H}_2} + y_{\text{H}_2\text{O}})n = n_{\text{H}_2,\text{F}} \quad (6)$$

$$(y_{\text{CO}}/2 + y_{\text{CO}_2} + y_{\text{H}_2\text{O}}/2)n = n_{\text{O}_2,\text{F}} \quad (7)$$

$$(y_{\text{CH}_4} + y_{\text{CO}} + y_{\text{CO}_2})n = Xn_{\text{C},\text{F}} \quad (8)$$

$$ny_{\text{N}_2} = n_{\text{N}_2,\text{F}} \quad (9)$$

By Dalton's law,

$$y_{\text{CO}} + y_{\text{CO}_2} + y_{\text{H}_2} + y_{\text{H}_2\text{O}} + y_{\text{N}_2} + y_{\text{CH}_4} = 1 \quad (10)$$

For a given gasification experiment $n_{\text{H}_2,\text{F}}$, $n_{\text{O}_2,\text{F}}$, $n_{\text{C},\text{F}}$, $n_{\text{N}_2,\text{F}}$, T_b and X are known. K_1 and K_2 can be calculated knowing T_b . Equations (4) to (10) were solved by a nonlinear equation routine to yield exit gas compositions, y_{CO} , y_{CO_2} , y_{H_2} , y_{CH_4} , $y_{\text{H}_2\text{O}}$, and y_{N_2} , as well as n , the total molar flow.

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